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Abstract

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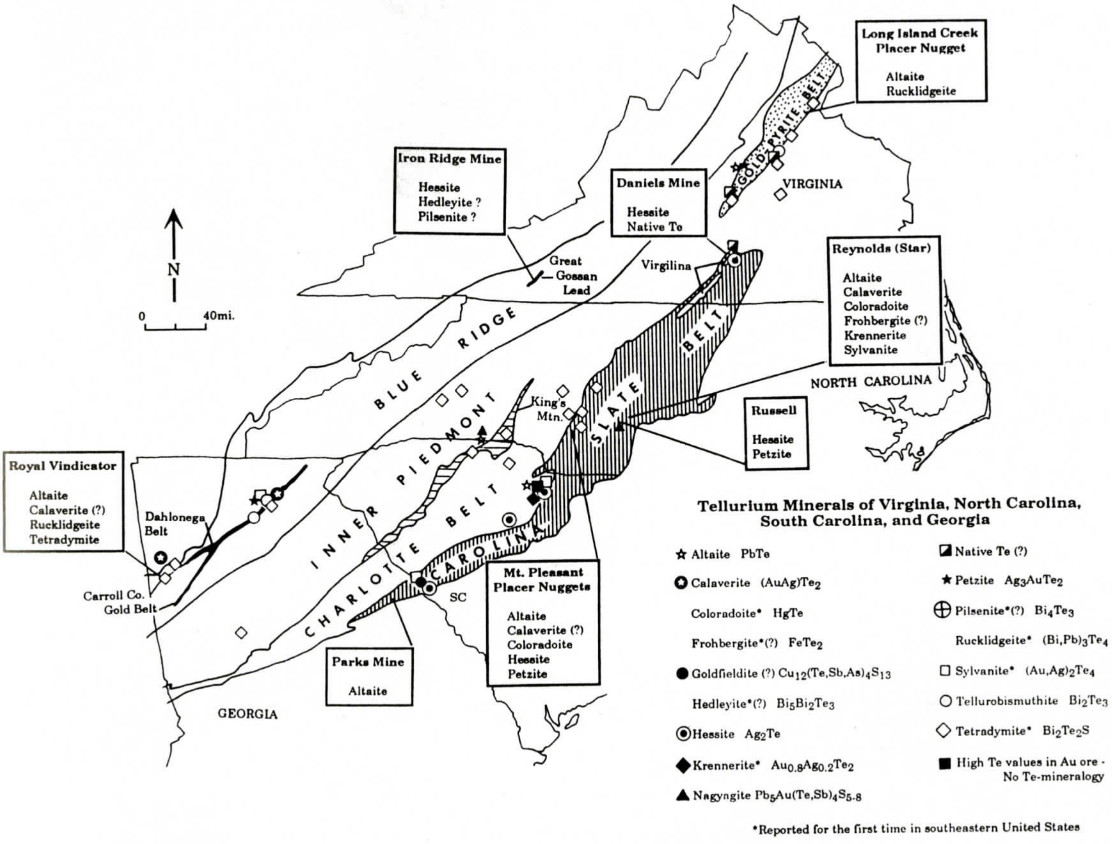
SOUTHEASTERN GEOLOGY



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INTERSECTION OF THE BLUE RIDGE FAULT WITH DUCTILE DEFORMATION ZONES IN THE BLUE RIDGE BASEMENT

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ABSTRACT

In southwestern Virginia, the Blue Ridge fault is a subhorizontal, brittle thrust fault that generally places Grenvillian basement and its Chilhowee Group cover sequence over unmetamorphosed Paleozoic sedimentary strata of the Valley and Ridge Province. Brittle deformation, including development of breccia and loss of cohesion in shear zones, characterize the thin fault zone. At the James River Gap, the trace of the Blue Ridge thrust turns southeast and passes into the internal part of the Blue Ridge Province, and no longer serves as the boundary between the Blue Ridge and Valley and Ridge Provinces.

Within the Blue Ridge Province, zones of ductile and cataclastic deformation define a braided pattern through a much less-deformed Grenville-age protolith. The Blue Ridge thrust intersects and truncates the northwestern edge of these zones of ductile and cataclastic deformation near the James River. The basement gneiss and its cover contain evidence of a complex history of deformation. Following origin of the Grenville-age basement protolith, zones of mylonite and augen gneiss containing granitoid boudins and lense-shaped masses formed in the basement. The augen gneissgneiss and cataclasite were later intruded by quartzo-feldspathic veins which were extended parallel to the foliation. Along the northwestern edge of the zone of ductile deformation, the mylonite and augen gneiss were folded, and a new but poorly developed foliation that cuts thin leucocratic veins formed. Folding and thrusting of the cover rocks and development of a spaced cleavage in the basement rocks accompanied Paleozoic emplacement of the Blue Ridge thrust.

INTRODUCTION

The objectives of this paper are: a). to document the character and location of the traces of the Blue Ridge fault and the zones of ductile and cataclastic deformation in the Blue Ridge Province where these structural elements intersect northwest of Big Island, Virginia, and b). to present evidence for the sequence of events indicated by the mesoscopic features in these deformation zones.

The name Blue Ridge fault encompasses portions of the system of thrust faults located along the northwestern edge of the Blue Ridge between Alabama and central Virginia. Grenville-age basement gneiss and/or units of the Chilhowee Group (Table 1) lie along the leading edge of the hanging wall of the Blue Ridge thrust sheet. These rocks are thrust onto lower Cambrian units, generally the Waynesboro (Rome) or Elbrook Formations. On the geologic and tectonic maps accompanying volume F-2 of the DNAG series (Rankin and others, 1989), major thrust faults appear along most of the northwestern edge of the Blue Ridge. Some authors include the Holston Mountain and Great Smoky faults, which occupy a structural position comparable to that of the Blue Ridge thrust, as part of the Blue Ridge thrust system. Parts of the Great Smoky fault system have Mississippian-age units in the footwall proving that this part of the system involved late Paleozoic thrusting. From Alabama to central Virginia, one or more faults are recognized as continuous thrusts along the northwestern flank of the Blue Ridge between the Blue Ridge basement and the Pulaski thrust. Farther north, discontinuous thrusts occur along portions of the Blue Ridge flank. In central Virginia, the

Table 1. Stratigraphic Column

Waynesboro (Rome) Formation	(300-400m)	Shale, limestone, and dolomite
Shady (Tomstown) Dolomite	(300-500m)	Dolomite and limestone
Chilhowee Group		
Antietam (Erwin) Formation	(200m)	Orthoquartzite
Harpers (Hampton) Formation	(300-500m)	Shale, graywacke, and sandstone
Weverton (Unicoi) Formation	(50-250m)	Sandstone, granule and conglomerates, graywacke, and shale
Loudoun Formation (Lower Unicoi)	(0-70m)	Purple slate, phyllite, shale, volcanics
Catoctin Formation	0-500+m)	Greenstone, purple slate, phyllite, granule conglomerate, volcanics
---nonconformity [1]---		
Blue Ridge Basement Complex		
Lovingston massif		Layered granulite gneiss, charnockite-suite plutons, and dioritic rocks intruded by granites
Pedlar massif		Layered granulite gneiss and charnockite-suite plutons

[1] The stratigraphic position of this nonconformity rises toward the northwest. It lies between the Weverton (Unicoi) and Grenville gneiss at the western flank of the Blue Ridge and between the Catoctin Formation and Grenville gneiss in the most internal exposures.

only stratigraphic control on the age of movement on the Blue Ridge thrust indicates that it is younger than Early Cambrian. Because the geometry of the Blue Ridge thrust and the direction of tectonic transport is consistent with the folding and faulting that affects rocks of late Paleozoic age in the Valley and Ridge, the Blue Ridge fault is generally considered to have been active during Alleghanian deformation.

Near Glasgow, Virginia, the trace of the Blue Ridge thrust swings east from a position along the northwestern flank of the Blue Ridge and passes to a more internal position in the Blue Ridge.

Near where the Blue Ridge Parkway crosses the James River, the Blue Ridge fault intersects a zone of ductile deformation within Grenville-age gneiss. Ductile deformation refers to modification of original textures by predominantly plastic flow due to recrystallization; cataclastic deformation refers to modification caused primarily by brittle fracturing, crushing, and comminution (Simpson, 1992). Many of the cataclasites in this part of the Blue Ridge appear to be transitional. They formed without loss of cohesion. Brittle failure of some mineral components was accompanied by recrystallization of others.

Zones of ductile and cataclastic deformation have long been recognized in the Blue Ridge Province. Working concurrently, Gathright and others (1977), and Bartholomew (1977) assigned the name Rockfish Valley fault to the northwestern edge of a wide fault zone exhibiting ductile and cataclastic deformation in the basement gneiss in the Waynesboro East, Greenfield, and Sherando quadrangles. Later Bartholomew and Lewis (1984) restricted the name Rockfish Valley fault to the principal fault within that zone that separates two basement massifs named the Pedlar and Lovingston massifs by Bartholomew and others (1981). Sinha and Bartholomew (1984) concluded that, in general, rocks of the Lovingston massif, located east of the Rockfish Valley fault, contain orthopyroxene ± amphibole assemblages formed at a slightly higher crustal level than those located west of the fault which contain orthopyroxene and garnet assemblages. In an alternative interpretation, Evans (1991) concluded that these basement massifs differ from one another because more water was accessible to the Lovingston than to the Pedlar massif during Paleozoic metamorphism and to a lesser extent during Taconic deformation.

Bartholomew and Lewis (1984) linked the Rockfish Valley ductile deformation zone in the northern and central portions of the Blue Ridge to the Fries and other faults of southern

Virginia and adjacent North Carolina as a single thrust system. The uncertain connection between the Rockfish Valley and Fries faults lies in the area described in this paper. Part of that uncertainty concerns the relationship between the Blue Ridge thrust and the ductile deformation zones which converge in the area of the James River Gap.

TRACE AND GEOMETRY OF THE BLUE RIDGE FAULT IN THE STUDY AREA

In central Virginia, the leading edge of the Blue Ridge thrust is subhorizontal (Figure 1 and 2). The thrust sheet has been breached by erosion in the Goose Creek Valley (Henika, 1981; Bartholomew and others, 1982) and in Arnold Valley (Bloomer and Werner, 1955; Spencer, 1969, 1993). Chilhowee Group rocks are present at the leading edge of the thrust

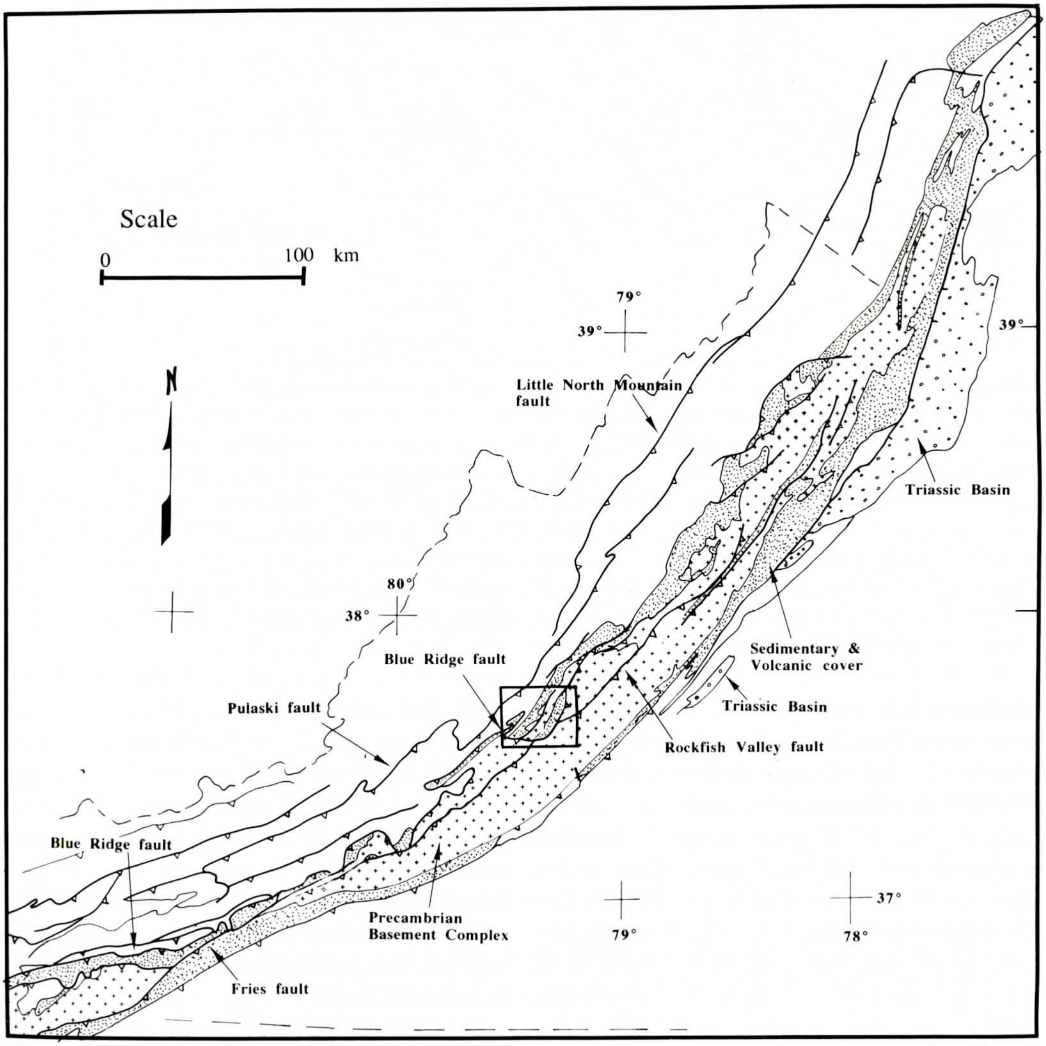

Figure 1. Sketch map of the Blue Ridge in Virginia. The Precambrian Blue Ridge basement complex (shown by + symbols) is undivided; late Precambrian and Cambrian clastic sedimentary rocks and associated volcanics (stippled) are undivided; Triassic sedimentary rocks are shown by open circles; all other rocks are undifferentiated. The area described in this paper is outlined. (simplified and modified after Rankin and others, 1989).

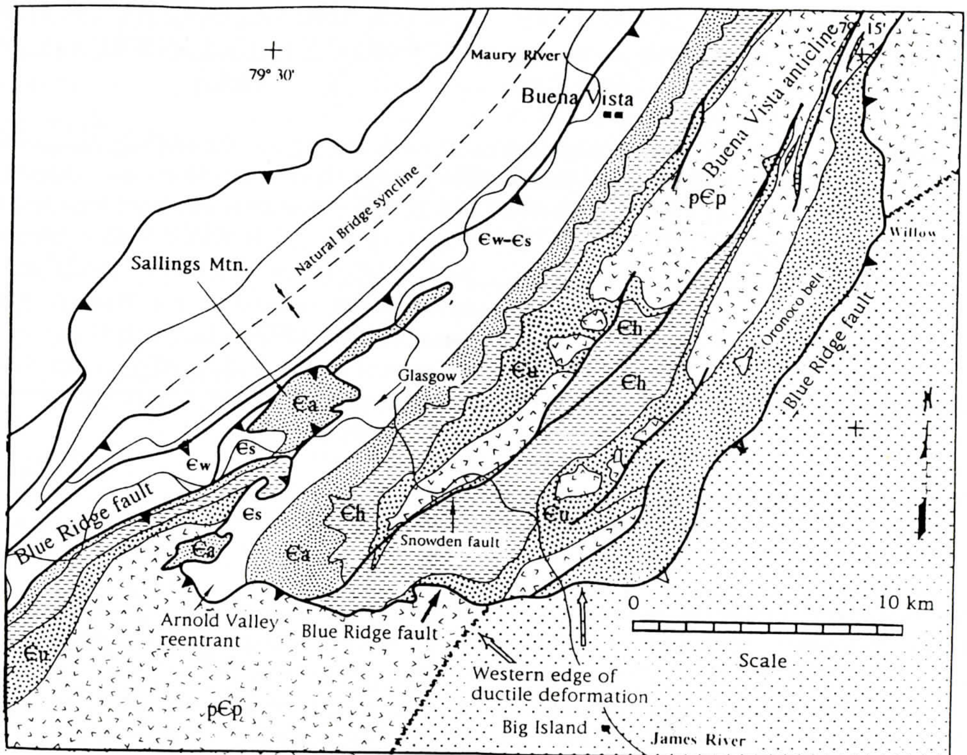

Figure 2. Tectonic sketch map of the northwestern flank of the Blue Ridge in the vicinity of the James River. Precambrian basement rocks are subdivided into two parts -- the Pedlar massif (v pattern) is largely composed of charnockitic rocks and granulite gneiss and the Lovingston massif (+ pattern) includes late Precambrian granites, diorites, quartzo-feldspathic veins, and quartz veins as well as charnockitic rocks and granulite gneiss. A number of zones of ductile deformation are present in the Lovingston massif. Thrust faults are indicated by heavy lines. Units of the Chilhowee (Antietam, Harpers, and Weverton (also Unicoi) Formations are distinguished by patterns. The Oronoco belt contains the Catoctin Formation and sedimentary rocks that resemble the Harpers and Weverton Formations. The younger sedimentary cover rocks in the Valley and Ridge are unadorned and largely undifferentiated. (Compiled from geologic maps by Spencer, 1968 and in press, and unpublished mapping by the author).

sheet, but the thrust sheet also carries Precambrian crystalline basement which is exposed above Waynesboro shale in the Goose Creek Valley reentrant and above Shady Dolomite at Arnold Valley. Recent mapping between Buchanan and Glasgow, Virginia demonstrates that the Blue Ridge thrust lies not between Grenville basement and the Chilhowee as previously mapped (Spencer, 1969), but west of the Chilhowee outcrop belt (Spencer, 1993, 1994). Only discontinuous faults with small displacements lie between the basement and the Chilhowee, and within the Chilhowee.

At Sallings Mountain, near Glasgow, Virginia, the Blue Ridge thrust defines a klippe composed of the Antietam Formation and Shady Dolomite (Figure 2). Northeast of Sallings Mountain and Arnold Valley, the hanging wall of the Blue Ridge thrust sheet has been eroded away, and a large basement-cored, southwest-plunging anticline known as the Buena Vista anticline (Figure 2) forms the northwestern flank of the Blue Ridge. This anticline plunges beneath the Blue Ridge thrust in Arnold Valley.

Near the northwestern edge of the Blue Ridge thrust sheet, the fault cuts through at least 1500 m of cover rocks. The fault rises from within the Grenville basement through the Catoctin Formation, Chilhowee Group, and

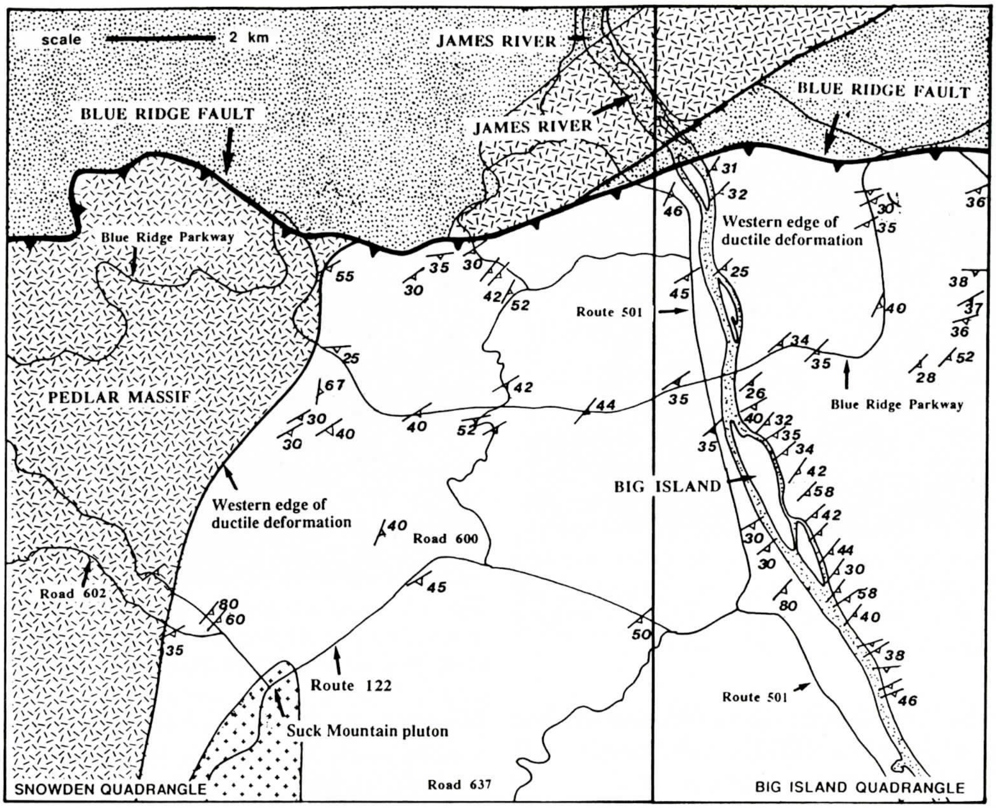

Figure 3. Geologic sketch map of the area near the intersection of the Blue Ridge thrust and the western edge of the zone of ductile deformation. Chilhowee units (dot pattern) are undifferentiated; rocks of the Lovingston massif are unadorned; rocks of the Pedlar massif are indicated by random dashes. The approximate border of the late Precambrian Suck Mountain pluton is indicated.

Shady Dolomite into the Waynesboro Formation. Because the thrust sheet carries basement gneiss over the Buena Vista anticline, the thrust must rise from a position within the crystalline basement on the southeastern side of the Buena Vista anticline.

From the Sallings Mountain klippe, the trace of the Blue Ridge thrust continues around the southern edge of Arnold Valley and intersects the northwestern edge of the zone of ductile deformation near the Blue Ridge Parkway southwest of the James River (Figure 3). From this junction, the Blue Ridge fault and the ductile deformation zone continue to the northeast. The two zones are more or less coincident for nearly 18 km. The Blue Ridge fault diverges from the zone of ductile deformation south of U.S. Highway 60. Evans (1991) traced the Blue Ridge thrust through the Precambrian crystalline rocks to where it emerges along the northwest flank of the Blue Ridge south of Waynesboro, Virginia. Bartholomew and others (1991), identified three faults in this area: the Back Creek, the Humpback Mountain, and the Rockfish Valley. As defined by Bartholomew (personal communication, 1992) the Back Creek fault is the probable northern continuation of the Blue Ridge thrust.

CHARACTER OF ROCKS IN THE BLUE RIDGE FAULT ZONE

The zone of brittle deformation along the frontal Blue Ridge thrust is only a few meters thick. Along the northwestern edge of the

Figure 4. Breccia formed along the northwestern edge of the Blue Ridge thrust. Sandstone clasts were derived from the Antietam Formation. The large fragments are approximately 8 cm wide.

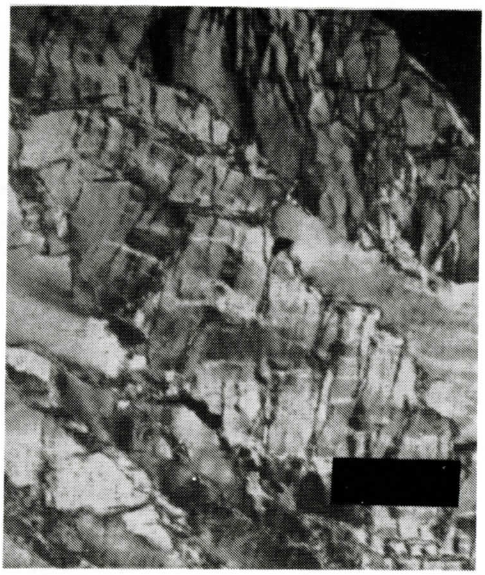

Figure 5. Deformed granules and pebbles in fragments of the Unicoi Formation found within breccias along the trace of the Blue Ridge thrust.

thrust sheet, the Antietam Formation lies near the edge of the thrust in the hanging wall. Slightly deformed limestone, dolomite, or shales of the Shady or Waynesboro Formation compose the footwall rocks. At these localities, intensely fractured quartzites lie above fault-zone rocks composed of breccia (Figure 4). Some quartzite is ground to a microbreccia, but most of it consists of coarse fragments some of which are more than 10 cm across. Much of the breccia is cemented by secondary iron oxides (primarily a mixture of goethite with some manganese). Some of the clasts in the breccia are from Weverton (Unicoi) quartzite, but none are basement gneiss.

Exposures of the fault zone are rare, but a number of exposures of rock within a few meters of the fault zone can be examined. West of its intersection with the ductile deformation zone, none of the gneiss close to the fault plane exhibits strong deformation in either the hanging wall or footwall, irrespective of the rock types juxtaposed on the other side of the fault. None of these gneiss exhibit evidence of plastic flow or even intense fracturing. In contrast, quartzites of the Antietam and Harpers Formations located near the fault plane at Sallings Mountain and in Arnold Valley in both the hanging wall and footwall of the fault are intensely fractured. On the east side of Arnold Valley, the Weverton quartzite has not lost cohesion, but pebbles and granules of quartz in the Weverton are shattered and elongated in a northwest-southeast direction by movements along fractures (Figure 5). Pressure solution has taken place along the contact of some grains and the rock is tightly cemented. Breccias located in Arnold Valley contain fragments of these strongly deformed Weverton quartzites.

TRACE AND GEOMETRY OF DUCTILE DEFORMATION ZONES IN THE BLUE RIDGE BASEMENT

Many authors (Bloomer and Werner, 1955; Hamilton, 1964; Follo, 1979; Haley, 1979; Brown and Spencer, 1981; Waterbury, 1987; Bowring, 1987; Spencer and others, 1989; Spencer and Waterbury, 1987, Spencer in Glover and others, 1994) (Figure 2) have mapped fault zones and ductile deformation zones within the Blue Ridge in the vicinity of

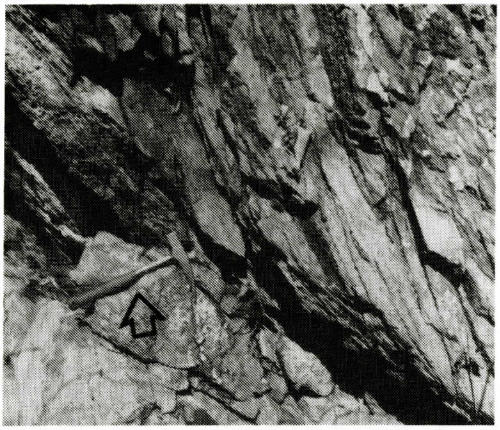

Figure 6. Late stage brittle shear zone and fracture cleavage developed in gneiss in the zone of ductile deformation. This zone which is several kilometers east of the Blue Ridge thrust resembles deformation along the Blue Ridge thrust where it cuts gneiss. Note the hammer for scale.

the James River. A sharp, well-defined fault boundary exists where the basement is in thrust contact with cover rocks. Along this boundary, basement gneiss in the hanging wall exhibits mylonitic foliation or augen textures indicative of ductile or cohesive-cataclastic deformation (Figure 2). The northwestern edge of the ductile deformation zone is commonly less distinct and more difficult to follow where the trace lies within basement rocks. Massive Precambrian rocks, part of the Pedlar massif, located northwest of the ductile deformation zone consist mainly of granulite gneiss, porphyritic charnockite, and minor amounts of granitoid. The rocks in and southeast of the zones of ductile deformation have a more complex history than the rocks of the Pedlar massif. A greater variety of rock types is present, and they exhibit many mesoscopic structural features that are absent northwest of the zone of ductile deformation.

Thomas Gathright II (personal communication, 1991) describes the deformation zone between the Pedlar and Lovingston massifs as transitional in the Waynesboro East quadrangle. Similar, poorly defined boundaries exist along the Rockfish Valley ductile deformation zone in Albemarle County, Virginia where it is difficult to delineate the footwall and hanging wall for this zone (Christopher Bailey, personal communication, 1992). A boundary of this type is present southwest of the James River where mylonitic gneiss are not continuously exposed. Numerous zones of ductile or cataclastic deformation appear near the James River, but away from the river exposures are poor and individual zones could not be traced. These do not appear to be narrow, distinct fault zones with great lateral continuity. They are better described as zones of varying width that form a braided or anastomosing pattern around less deformed plutons and smaller masses of protolith.

Zones of brittle deformation, probably related to Alleghanian deformation, occur southeast of the western edge of the ductile deformation zones. One such zone is illustrated in Figure 6.

CHARACTER OF THE DUCTILE DEFORMATION ZONES

Textural Variations Within and Across the Deformation Zones

The most continuous exposures across the zones of ductile and cataclastic deformation in the basement occur where the James River cuts through them near Big Island, Virginia (Figure 3). Numerous deformation zones occur along the river for a distance of nearly 10 km. Rock fabric within these zones varies from one zone to the next (Figures 7 and 8), but these changes are not progressive nor systematic. Augen gneiss and deeply weathered zones of fine cataclasite are most widespread, but in the terminology of Wise and others (1984) protomylonite, mylonite, ultramylonite, blastomylonite, augen gneiss, phyllonite, and cataclasite occur close together as parallel or subparallel units. These zones of highly deformed basement rocks (Figure 8) separate bodies of undeformed or slightly deformed charnockite, granulite gneiss, or granitoid rocks that occur as boudins or lens-shaped

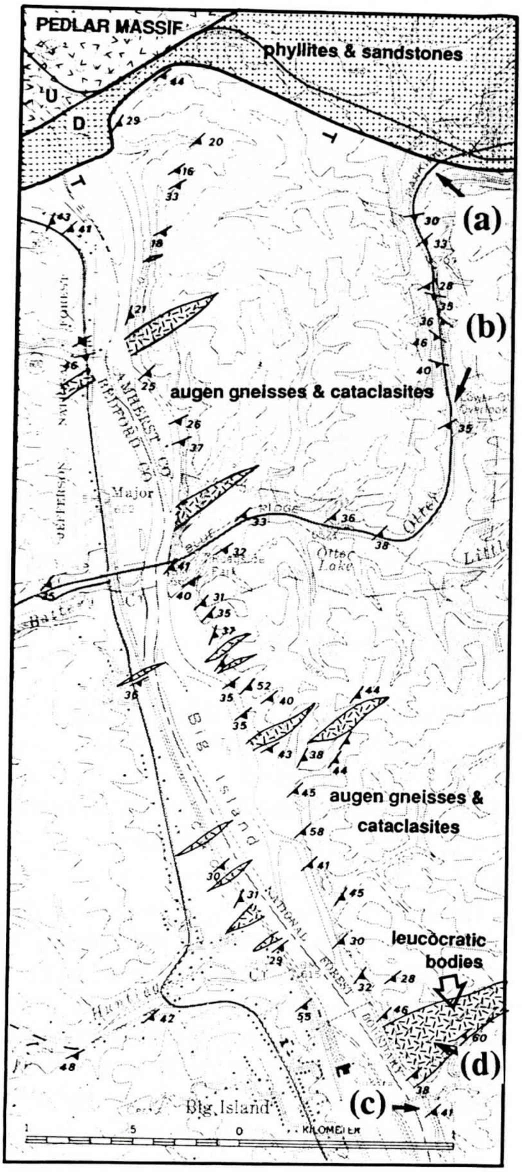

Figure 7. Sketch map of the ductile deformation zones exposed along the James River near Big Island, Virginia. Examples of representative rocks in the zone of ductile deformation are indicated. (a), folded mylonite from a locality near the Blue Ridge Parkway where the Blue Ridge thrust cuts the zone of ductile deformation. (see Figure 10C); (b), augen gneiss with drawn out porphyroclasts (see Figure 8B); (c), slightly deformed coarse-grained granitic rock in one of the lens-shaped bodies in the ductile deformation zone. (see Figure 8D); (d), small boudin composed of granitic rock enclosed in mylonite. (See Figures 12A and 12B).

masses. These less deformed bodies were more competent during deformation than were the surrounding augen gneiss and cataclasite. Boudins in augen gneiss are commonly surrounded by a border of finely laminated mylonite or cataclasite indicating that these borders are zones of extreme deformation formed as the boudins moved through the gneiss.

Lateral variations in the thickness and texture of the deformed zones occur along strike. Variations occur in the width of individual zones of mylonitic rocks, the total width of the deformed zones, and the thickness of the intervening zones of undeformed rock. Although exposures away from the river are inadequate to allow precise mapping, the zone of ductile deformation is much wider and more continuous along the James River than it is farther southwest where bands of strongly deformed rock are narrow, widely separated, and poorly exposed. The Suck Mountain pluton, a Precambrian granitoid body and probable source of the material in the boudins and granitoid lenses in the ductile deformation zone, lies along the trend of the deformation zones southwest of the James River. Rocks of this pluton are much less deformed than the immediately surrounding country rock. The presence of this competent body probably accounts for the overall reduction in width of the zone of deformation in this area.

The dominant mylonitic and gneissic foliation strikes northeast, dips southeast, and roughly parallels the cleavage developed in the cover rocks (Figure 9). This trend swings to a more southerly direction on the west side of the James River where the strike of foliation is oblique to the northwestern edge of the deformed zone. Lineations defined by mineral elongation in the plane of the dominant foliation trend N20-40W. These lineations are slightly oblique to the northwestern edge of the deformation zone (Figs. 3 and 9).

Mesoscopic Structural Features and Kinematic Indicators

The most prominent of the mesoscopic structural features in the zone of ductile deformation are: a). strongly foliated mylonite (Figure 8A); b). rotated and elongated sigma-type porphyroclasts in augen gneiss (Figure 8B); c). mesocopic folds formed in mylonite and augen gneiss (Figure 10); d). boudins (Figure 12); e). extended leucocratic veins (Figure 13); f). spaced cleavage that cuts the mylonitic and gneissic foliation (Figure 14); g). brittle shear fractures that cut the mylonitic rocks (Figure 6).

A few mesoscopic folds with northwestern vergence (Figure 10) occur in the mylonite and augen gneiss. Although these folds occur near the trace of the Blue Ridge thrust where it cuts into and coincides with the deformed zone, the strain that produced most of these folds is incompatible with the type of brittle deformation seen in the Blue Ridge thrust. This folding took place at sufficiently high temperature and pressure for folds to develop without formation of fractures or bedding parallel slip. Hence, the folding is thought to have formed earlier than emplacement of the Blue Ridge thrust sheet. Thus multiple or progressive, post-mylonite, phases of movement took place in the deformed zone. The earlier phase took place at higher temperature and pressure than the later phase which is marked by brittle failure and development of breccia. The growth of new micas parallel to the older mylonite foliation supports the idea that a post mylonite thermal event may have accompanied deformation.

Rotated porphyroblasts and sigma-type porphyroclasts in augen gneiss have been used by a number of investigators to determine vergence in ductile deformation zones. Waterbury (1987), Sessions, (1991) and Grigg (1991) as well as the author have studied these features within the area of this investigation. Rotations of feldspar porphyroblasts showing both northwest and southeast vergence are present. Those indicating northwest vergence are more common. In studies of exposures along U. S. Highway 60, Sessions and Grigg found evidence of

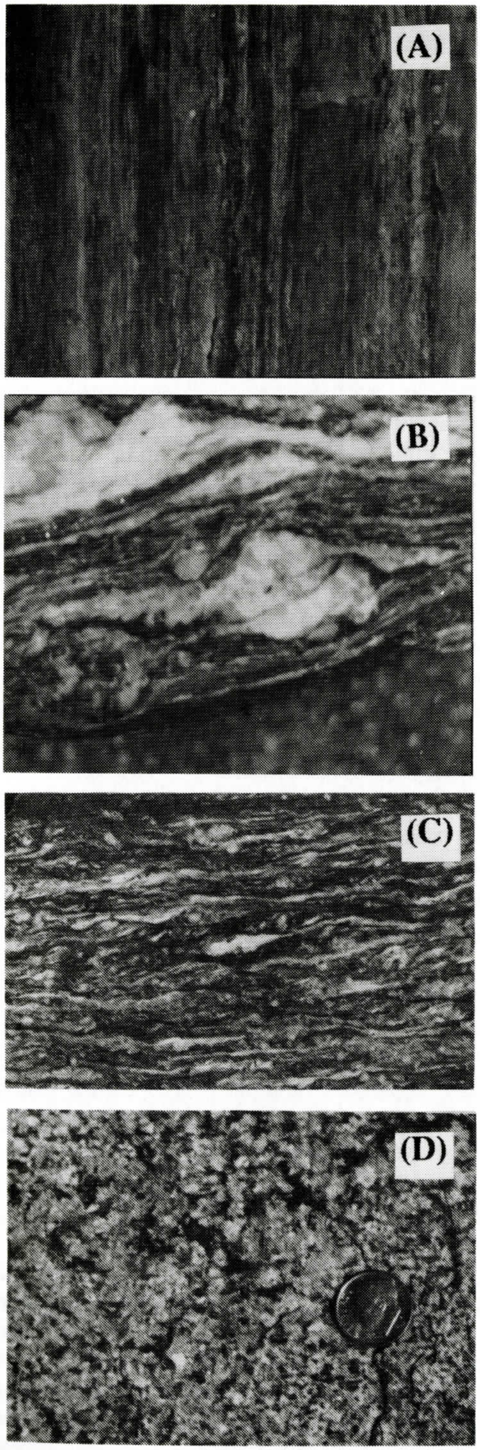

Figure 8. Textural variations of rocks in the ductile deformation zone. (A) mylonite; (B) augen gneiss showing sigma-type augen drawn out and indicating northwest vergence; (C) strongly deformed augen gneiss; (D) relatively undeformed granitoid body in the ductile deformation zone.

two coaxial foliations, an older foliation with southeast dips of 50-70 degrees and a younger foliation with 25 degree southeast dip. Their analysis suggest that porphyroblasts associated with the older foliation indicate southeast vergence while a northwest vergence is associated with the younger foliation. This interpretation is in agreement with the results of studies by Bailey and Simpson (1993) over a much larger area.

Sigma-type porphyroclasts showing both northwest and southeast vergence occur close together within a single outcrop. In a mass of rock subjected to simple shear under conditions promoting ductile behavior, all crystals should exhibit the same sense of rotation if the sense of shear is uniform throughout the rock. However, if the shear is not uniformly distributed through the rock, lenses of material may lag behind. In this case, rotations at the top and bottom of the lens would exhibit opposite senses of rotation. This effect may be responsible the presence of both senses of rotation seen in this area.

Coarse-grained quartz and feldspar pegmatites and milky quartz veins occur as lenses, sills, or stringers within the gneiss in the deformed zones. Some of these bodies predate and others postdate the mylonite. The foliation wraps around the pegmatite shown in Figure 11. Crystals at the edge of the pegmatite are flattened parallel to the foliation proving that the pegmatite was present at the time the foliation formed. Deflection of the foliation around the main body of coarse crystals indicates that these leucocratic rocks resisted development of mylonite. Veins of quartz and feldspar that cut across the mylonitic foliation prove that some

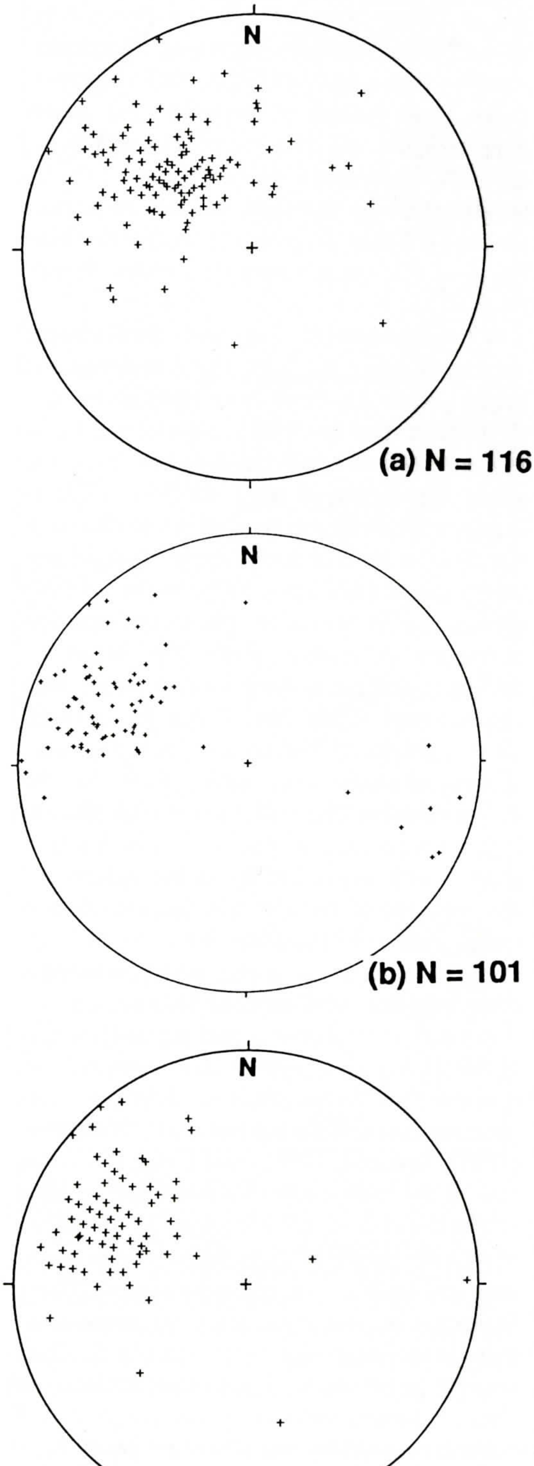

Figure 9. Plots of foliation within and near the ductile deformation zone. a). Mylonitic foliation in Precambrian rocks near the northwestern edge of the zone of ductile deformation. b). Cleavage in greenstones of the Catoctin Formation exposed near the zone of ductile deformation. c). Cleavage in slightly metamorphosed sedimentary rocks of the Catoctin and Chilhowee Group exposed near the zone of ductile deformation. All plots are in the lower hemisphere; the number of measurements is indicated for each plot.

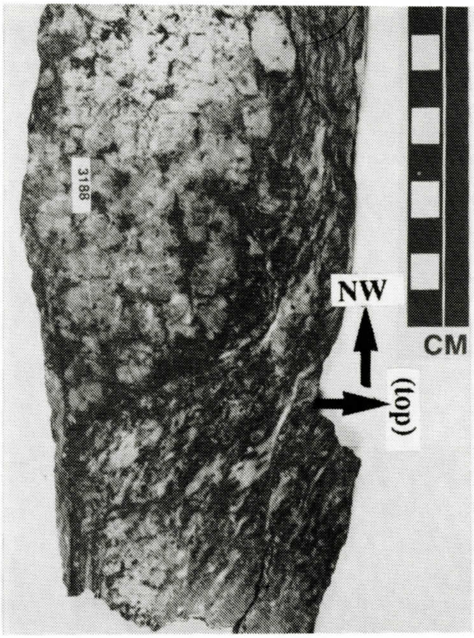

Figure 11. Mylonitic gneiss wrapping around a coarse-grained portion of the protolith near the northwestern edge of the zone of ductile deformation. This sample is from a locality near the northwestern edge of the late Precambrian Suck Mountain pluton.

of these veins were intruded after the mylonites had formed.

Boudins are present in some of the pegmatites and coarse granitoid bodies (Figure 12), and some leucocratic veins (Figure 13) have been elongated by offsets along fractures. Both of these features result from extension of the less ductile rock. Near Big Island, Haley (1979) found elongate, leucocratic inclusions within the augen gneiss and fine grained cataclasite. Most are parallel to the foliation, but some cut across the foliation at small angles. Extension of these bodies may result from drag effects during or after development of the foliation. The local extension may be a result of shearing under regional compression rather than a result of regional extension.

Figure 10. Examples of folded augen gneiss (A) and mylonitic foliation (B and C) in the Blue Ridge basement located east of the trace of the Blue Ridge thrust and the western edge of the zone of ductile deformation.

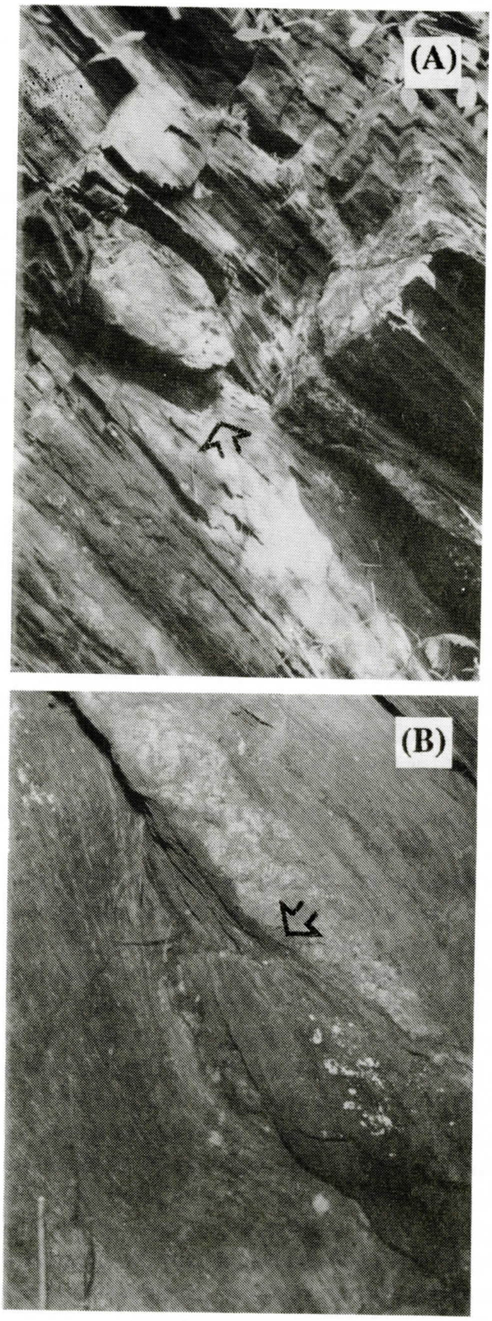

Figure 12. (A) Boudin formed in quartzo-feldspathic sill; (B) boudin-shaped lense of fine grained mylonite and cataclasite.

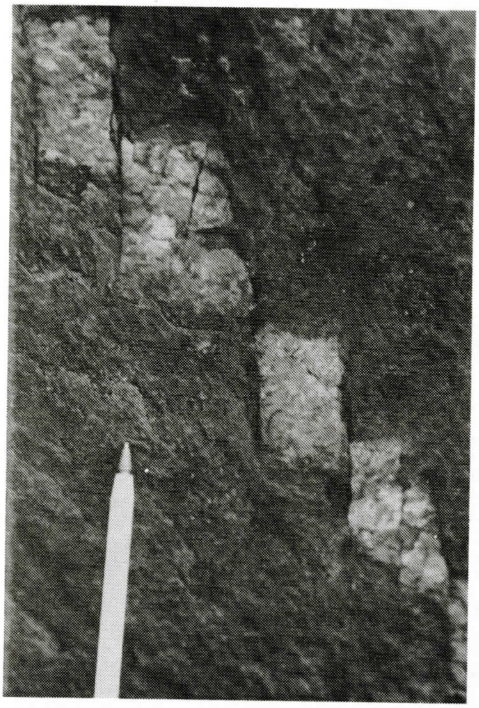

Figure 13. A southeast-dipping quartzo-feldspathic sill fractured and extended.

Closely spaced, brittle fractures, essentially a spaced cleavage (Figure 14) involving loss of cohesion, occur in some outcrops. These fractures trend northeast-southwest; and are subparallel to the trend of the mylonitic foliation. They exhibit low dips, in the range of 10-25 degrees southeast, compared with mylonitic foliation which dips in the range of 30-60 degrees. The style of deformation represented by the fracture cleavage is consistent with that associated with the emplacement of the Blue Ridge thrust sheet.

INTERSECTION OF THE BLUE RIDGE FAULT AND ZONES OF DUCTILE DEFORMATION IN THE BASEMENT

The Blue Ridge thrust intersects and truncates the northwestern edge of the ductile and cataclastic deformation zones in the Blue Ridge basement near the Blue Ridge Parkway (Figure 3). Along most of the zone in which the traces of the Blue Ridge thrust and the zone of ductile deformation coincide, basement mylo-

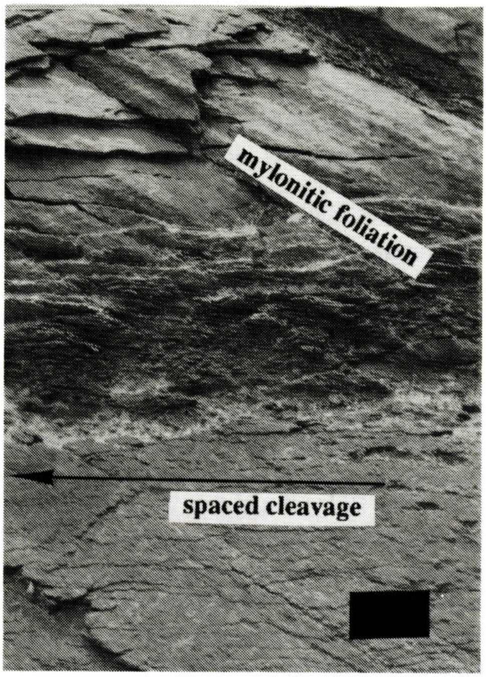

Figure 14. An example of spaced cleavage developed in mylonitic gneiss. The spaced cleavage cuts across the mylonitic foliation at a low angle. The bar is 10 cm. long.

nites and gneiss are thrust onto slightly metamorphosed shales, sandstone, pebble conglomerates, and greenstones of the Harpers, Weverton (Unicoi), and Catoctin Formations (Bowring, 1987; Spencer and others, 1989). The contact between basement and cover rock is well-exposed in a few places and can usually be located within a few meters. In most of the exposed sections, the contact between the mylonites and stratified rocks is structurally conformable with little indication of brittle faulting between them. At a few localities, brittle fractures and well-defined planes of movement containing slickensides and zones within which the rock has lost cohesion lie in this fault contact. More commonly the brittle deformation associated with the Blue Ridge thrust lies a few tens of meters southeast of the contact between mylonite gneiss and metasedimentry rocks. These field relationships suggest that the thrust contact between the rocks of the ductile deformation zone and metasedimentary rocks in the footwall predate brittle faulting associated with emplacement of the Blue Ridge thrust sheet. Thus, the position of the Blue Ridge thrust plane along this section of the fault followed the earlier fault contact between the ductile deformation zone and the underlying cover.

SEQUENCE OF EVENTS

Analysis of regional mapping and mesoscopic structural features in the area of this study indicate the following sequence of events:

1. The Grenville or pre-Grenville-age protolith which included intrusions of charnockitic and dioritic plutons into layered granulite gneiss formed first. Foliation in some of the charnockites suggest that these ancient gneiss record Precambrian-age ductile deformation.

2. Quartzo-feldspathic veins (Figure 13), and some larger granitoid bodies intruded the protolith before or early during development of mylonite and augen gneiss. These intrusions may be related to the Suck Mountain pluton located several kilometers southwest of the James River.

3. These veins and larger granitoid bodies were subsequently extended to form boudins and offset strings of blocks (Figure 12 and 13). Extension of these less ductile bodies was probably contemporaneous with development of mylonite and augen gneiss. That late or post-mylonite extension occurred is demonstrated by the presence of boudins containing disoriented bodies of mylonite (Figure 12). Tension gashes in some of the boudins indicates that the leucocratic rocks remained relatively brittle during this deformation.

4. Kinematic indicators in the augen gneiss (Figure 8) provide evidence of predominant northwest vergence; however, southeast vergence is indicated by some deformed porphyroclasts. Some workers conclude that this earliest fabric represents extensional strain with tops down to the southeast followed by a later deformation with northwest vergence that

resulted in the present form of the ductile deformation zone. However, proximity and similarity in orientation and texture of the sigma-type porphyroclasts indicating southeast and northwest vergence suggest that they may have formed simultaneously.

5. After or late in the development of the mylonitic foliation, local folding of the mylonite occurred (Figure 10). The vergence of the folds indicates northwest tectonic transport. The style of the folds indicates that they formed under higher pressure and temperature conditions than that associated with the Blue Ridge thrust. The fact that the folded mylonites rest on Catoctin and Chilhowee rocks provides a maximum age for the movement. Some of the rocks in the deformed zone exhibit cataclastic textures that formed under conditions that made it possible for fragmentation and comminution to take place without loss of cohesion. This deformation is less ductile than deformation that accompanied formation of the mylonite, but it is not as brittle as deformation in the basement that accompanied the emplacement of the Blue Ridge thrust. This cataclasis may represent a separate event, or it may have formed at a late stage in the development of the ductile deformation as the rocks in the deformed zone rose to higher crustal levels.

6. A second generation of leucocratic veins cut across the mylonitic foliation. Some of these are extended; others occurs along the fault contact between the mylonite or augen gneiss and the underlying metasedimentary rocks.

7. Development of low southeast-dipping zones of brittle shear (Figure 6) and spaced cleavage (Figure 14) followed formation of the mylonitic gneiss. The similarity in orientation of these brittle features with that of low southeast-dipping foliation that transects the mylonitic foliation in other places suggests that these formed at the same time. The development of these late stage shears and foliations was probably contemporaneous with movement and brittle deformation on the Blue Ridge thrust.

8. Brittle deformation occurred along the Blue Ridge thrust as it cut through the mylonitic gneiss and rose through the Pedlar massif into and through the Chilhowee Group cover. The Blue Ridge thrust and the northwestern edge of the zone of ductile and cataclastic deformation nearly coincide for about 18 kilometers.

9. During or following emplacement of the Blue Ridge thrust, the thrust sheet was arched as the Buena Vista anticline formed along the northwest edge of the Blue Ridge.

SUMMARY

The Blue Ridge thrust cuts through the Antietam Formation at depths favorable for brittle behavior of quartzite and development of breccia. At deeper levels along the fault, exposed toward the southeast, quartz pebbles and granules in the Weverton (Unicoi) Formation in the footwall are flattened and elongated. Quartz exhibits undulatory extinction; clasts are fractured and some are extended along en echelon fractures. Some of the fragments exhibit effects of pressure solution. The Blue Ridge fault zone is no more than a few meters thick. The gneiss in the hanging wall shows little indication of cataclasis and no evidence of ductile behavior. In contrast, where the Blue Ridge thrust cuts through and trends parallel to the ductile deformation zone, rocks on the hanging wall exhibit fabrics that are the product of both ductile and brittle behavior.

Zones of brittle deformation marked by loss of cohesion characteristic of the Blue Ridge thrust generally occur southeast of the contact between footwall metasedimentary rocks and hanging wall mylonite gneiss. Younger brittle deformation including cataclasis, brittle fracturing, and development of spaced cleavage is superimposed on rocks near the northwestern edge of the zone of ductile deformation which reveal a complex structural history that includes intrusion of leucocratic veins and lense-shaped granitoid bodies into the protolith, development of mylonitic foliation, formation of boudins, and other expressions of ductile deformation. A second phase of intrusion of veins of quartz veins and leucocratic pegmatites, and folding of the mylonitic foliation followed the earlier deformation.

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TELLURIDE MINERALIZATION OF THE SOUTHEASTERN UNITED STATES

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ABSTRACT

Telluride minerals, although rare and present only in relatively few localities, are known to commonly occur with gold. Thirty-six locations, including eight new telluride mineral ones, are now known in the southeastern United States (GA, SC, NC, VA). The most common telluride mineral reported in the literature for these locations is tetradymite (Bi_2Te_2S), but its identity is suspect in the older literature. Most of the tellurides are associated with gold-bearing quartz veins or lodes, but tellurides also occur in massive sulfide and disseminated gold deposits. Tellurides observed in this study are generally small (<10 - 250 microns) and are found as discrete grains or as inclusions in gold or in sulfide minerals. Telluride mineralization also transects geologic belts and is most often found in volcanics, volcaniclastics or their metamorphosed equivalents.

INTRODUCTION

The first report of telluride mineralization in the United States was by C.T. Jackson in 1848 when he noted lead, gold and tellurium in analyses of minerals from the Whitehall Mine in Spotsylvania County, Virginia. Additional localities were identified since then, but the latest compilation of telluride minerals in the southeastern United States, prior to the present study, is the work of Pardee and Park (1948) who summarized information on five telluride minerals in a total of 16 gold localities. Over the last ten years, several new telluride mineral localities have been reported that contain a variety of telluride minerals, mainly from producing gold mines.

The discovery of telluride minerals upon examination of samples from placer and lode gold occurrences in North Carolina and Virginia prompted the authors to search further as well as attempt to compile the literature regarding telluride minerals in the southeast. As a result, telluride minerals or new telluride mineralization have been identified at eight localities not previously noted in the literature. This paper presents a tabular compilation of all previously recorded and newly identified southeastern telluride mineral localities, the associated minerals, geological setting, and other pertinent information. To date, the localities identified occur in Georgia, the Carolinas and Virginia, and it is likely that additional localities will be identified. However, the rarity of telluride minerals, their small grain size and the difficulty of verifying the mineral present without microbeam analysis facilities will affect the availability of new data.

GENERAL GEOLOGY

Telluride mineralization in the southeast transects geologic belts and deposit types (Figure 1, Table 1). Hence, telluride minerals (Fig-

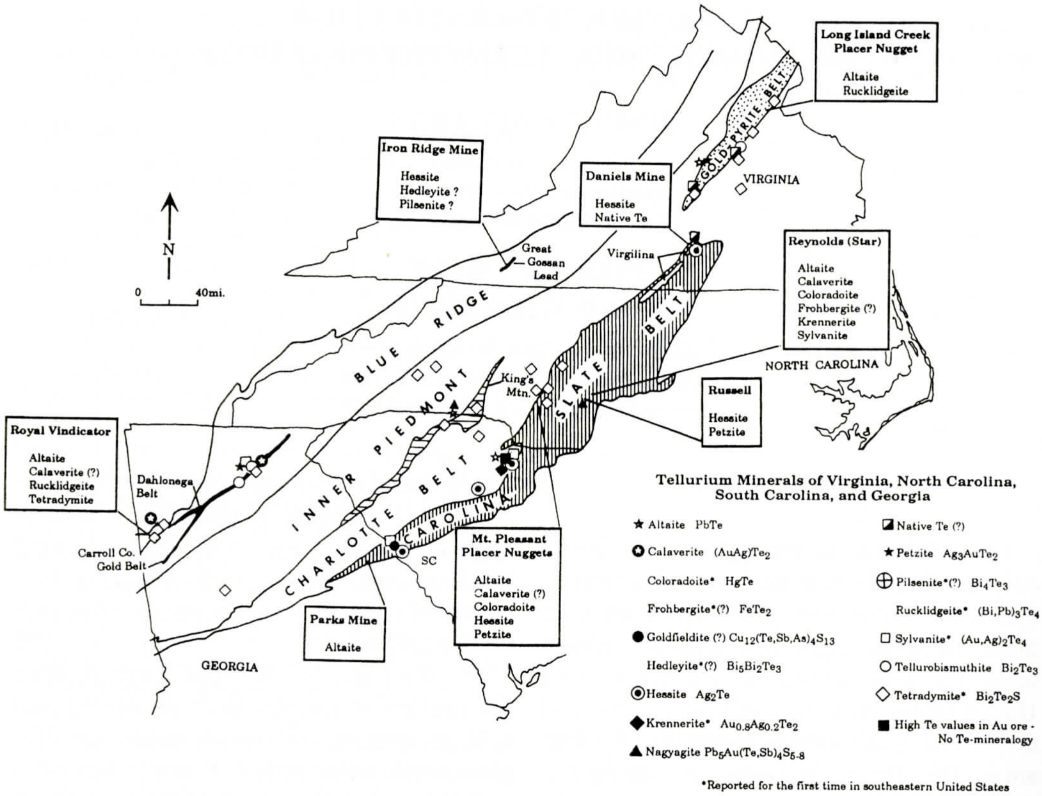

Figure 1. Telluride mineral locations of the southeastern, United States. Mines and minerals shown in boxes have telluride minerals that are identified for the first time in the literature other than in abstract form. * Telluride mineral reported for the first time in the southeast. ** Tetradymite - most common telluride mineral in southeastern U.S. (Note: Some of the reports of tetradymite might actually be tellurobismuthite or other Bi tellurides.)

ures 2-6) have been identified from massive sulfide deposits (Great Gossan Lead, Eastern Blue Ridge), disseminated gold deposits (Carolina slate belt), veins and lodes (Carolina slate belt, gold pyrite belt, Virgilina district, Inner Piedmont, Kings Mountain and Dahlonega belts), and nuggets in placer deposits (Long Island Creek, VA and the Mt. Pleasant area, NC). The most commonly reported telluride mineral in the literature of the 1800's is tetradymite, although work by Cook (1973; 1994) has shown that many of these original reports were in error and the mineral is actually tellurobismuthite or another bismuth-telluride mineral. Vein-type gold deposits appear to be the most common hosts for telluride minerals in the southeast. Telluride mineral grains observed in this study tend to be small (<10 - 250 microns), usually associated with gold and sulfide minerals and occur as inclusions disseminated in these associated minerals or as discrete grains (Table 1).

DISCUSSION

Telluride minerals for the new locations reported in this study were identified based on electron microprobe analyses performed with a CAMECA SX50 instrument and in a few instances by energy dispersive analysis with a CamScan II scanning electron microscope (Appendix 1). All analyses were done on polished sections or polished thin sections. The eight new locations or locations with new telluride minerals are shown in Figure 1 in boxes,

Table 1. Telluride minerals of the southeast: their locations and associated geologic information and references. Notes: 1. A question mark (?) beside a telluride mineral indicates that the mineral identified is in question either because of no chemical analyses provided in the literature, because the identification was done in the 1800's (Cook, 1973,1994), or there is not a complete set of the chemical analyses such as with the BiTe minerals from the Iron Ridge mine in Virginia. 2. The Drake mine listed by Pardee and Park (1948) as Polk Co. North Carolina is actually an occurrence in Polk County, Georgia.

Virginia

Mine Prospect/ Location by County	Telluride Mineral(s)	Associated Minerals	Geological Belt/ rock type(s)	Type of Deposit	Au Production	Reference(s)
Barnes/ Charlotte	Hessite (?)	bn, cc	CSB, Virgilina Dist./greenstone	Quartz vein		Laney, 1917; Johnson, 1994
Daniels/Charlotte	Hessite, Te	Au, cv, cpr, bn, mc, dg, anilite	CSB, Virgilina Dist./greenstone	Quartz vein		Johnson, 1983, 1994; Johnson, Craig, and Rimstidt, 1989; Sweet and Lovett, 1985
Iron Ridge Mine(Bumbarger Pit)/Carroll	Hessite, Hedeyite*(?), Pilsenite*(?)	po, py, cpy, sp, gn, supergene Cu - minerals	Great Gossan Lead/Shear zone in Lynchburg gneiss	massive sulfide		Callahan, Craig, and Bean, 1994; Luttrell, 1966
Long Island Ck/ Fluvanna (Note: Stocktown Tunnel mine and Page mine are on Long Island Creek.)	Altaite, Rucklidgeite*	single nugget	GPB	single nugget		Dietrich, 1990; Callahan, Craig, and Bean, 1994
Monroe/Stafford	Tetradymite (?)	Au, py	GPB/ quartz-sericite schist	Quartz vein		Dana, 1906; Luttrell, 1966
Morrow/Buckingham Tetradymite	Te (?)	py, Au, cpy, po	GPB/ quartz-sericite schist with bands and lenses of biotite and garnet	Quartz vein	260 troy pds. and $60,000 placer Au	Luttrell, 1966; Henwood, 1871
Moss/Goochland	Tetradymite	py, Au, gn, sp, cpy, cv, mc, tr, pyromorphite, vanadinite	GPB/garnetiferous quartz-sericite schist (HW) and hornblende schist (FW)	Quartz vein in shear zone	$20 - $25,000	Luttrell, 1966
Stocktown/Spotsylvania	Tetradymite		GPB	Quartz vein in shear zone		Genth, 1855; Pardee & Park, 1948
Tellurium/Fluvanna-Goochland	Te (?), Telluorobismuthite, Tetradymite (?)	py, Au, sp, Se, Ag	GPB garnetiferous quartz-sericite schist; fine-grained ferruginous quartzite	Quartz vein in shear zone	$250,000+	Genth, 1855; Good and others, 1977; Hotchkiss, 1881; Jackson, 1850; Luttrell, 1966; Taber, 1913; Palache and others, 1944
Whitehall/Spotsylvania	Bi, Te, Se-mineral (?), Te (?), Tetradymite (?)	py, Au, gn	GPB/chloritic schists or slate	Quartz vein	$1,800,000	Dana, 1906; Genth, 1868; Jackson, 1848; Luttrell, 1966

Mine Prospect/ Location by County	Telluride Mineral(s)	Associated Minerals	Geological Belt/ rock type(s)	Type of Deposit	Au Production	Reference(s)
Young American/ Goochland	Sylvanite (?), Tetradymite	py, Au, cpy, sp, Ag	GPB hornblende-biotite-chlorite, magnetite, gneiss; quartz-sericite-feldspar gneiss and schist, intra-layered with ferruginous quartzites	Quartz vein	1500 tons of ore	Luttrell, 1966; Taber, 1913

* New mineral for state of Virgina

Note: Taber, 1913 mentions Te (?) - gold ores of James River Basin in Buckingham, Cumberland and Powhatan Counties; however, no specified mines or minerals.

Note: Several of the native Te mineral reports and tetradymite reports may be one of the other Te-Bi minerals and Ag is not native silver but a by-product of other minerals production.

North Carolina

Mine Prospect/ Location by County	Telluride Mineral(s)	Associated Minerals	Geological Belt/ rock type(s)	Type of Deposit	Au Production	Reference(s)
Allen (Lalor)/ Davidson	Tetradymite(?)	py, cpy, Au, Ag	CSB / granite	Vein	$20 - 190/T	Genth, 1891; Nitze & Wilkens, 1897; Kerr, Hanna, 1893
Ashbury (Long Creek)/Gaston	Tetradymite (?)	py, Au, gn, sp, cpy, asp, carbonate of Bi	Kings Mt / chlorite schist	Vein	0 - 40 oz / T	Genth, 1891; Kerr & Hanna, 1893; Carpenter, 1972
Beck (David / Davidson	Tetradymite (?)	Au	CSB	Vein		Genth, 1875
Boger (Allen Boger) / Cabarrus	Tetradymite	Au, cpy	CB / diorite	Vein (?)		Genth, 1875; Pardee & Park, 1948
Carter / Montgomery	Nagyagite	Au, py	CSB / lapilli tuff	Vein and disseminated in silicified lapilli tuff	~ $100,000/$6 - 7 / T	Emmons, 1856; Pardee & Park, 1948; Powers, 1992
Cullen / Cabarrus	Tetradymite					Genth, 1875
Drake Mine /(?) Polk Co, Ga	Tetradymite (?)	Note: This mine is listed in Little, 1875 as located in Georgia. The North Carolina listing by Pardee and Park, 1948, p. 32 is a mistake.				Pardee & Park, 1948;Little, 1875
Gold Hill / Rowan	Tetradymite	Au, py, cpy, cc, gn, sp	CSB / chlorite - sericite phyllite	Veins in shear zone	~ $1,650,000 from all mines in area / $10 - $385 / T	Cook, 1973, 1994; Pardee & Park, 1948
J.C. Mills / Burke	Tetradymite (?)	Au	IP (South Mtn.) gneisses, schists	Vein	~ $1,000,000 mainly placer	Genth, 1875; Carpenter, 1972
Kings Mt / Cleveland	Altaite, Nagyagite	Au, py, po, cpy, gn, sp, boulangerite	KMB / siliceous-dolomitic marble; chlorite, mica schist	Vein in shear zone	~ $1,000,000 $3/ Ton	Genth, 1875; Carpenter, 1972; Supplee, 1986
Capt. Kirksey / McDowell	Tetradymite (?)		IP (South Mtn.) / gneisses; schist	Vein		Genth, 1875

Mine Prospect/ Location by County	**Telluride Mineral(s)**	**Associated Minerals**	**Geological Belt/ rock type(s)**	**Type of Deposit**	**Au Production**	**Reference(s)**
Mt. Pleasant area ?? / Cabarrus	Altaite, Coloradoite*, Hessite, Petzite, Rucklidgeite*	Au	CSB	Placer nuggets from streams in the area		Callahan, Craig, and Bean, 1994
Phoenix / Cabarrus	Tetradymite	Au, py, cpy, gn, ba	CB - CSB	Vein in shear zone	~ $400,000	Genth, 1875; Genth, 1891; Pardee & Park, 1948; Carpenter, 1976
Reynolds (Star) / Montgomery	Altaite, Calaverite*, Coloradoite*, Frohbergite, (?)*, Krennerite*, Sylvanite, Tellurantimony (?)	Au, py, cpy, sp, bn, cc, mb, native Fe, hm	CSB	6-8' wide fault zone		Emmons, 1856; Kiff, 1966; Carpenter, 1976; Stephens, 1982
Russel / Montgomery	Hessite, Petzite	Au, py, po, cpy	CSB / argillites, felsic-lapilli, fragmental, tuffs	Silicified lodes and breccias	~ $500,000/ 0 - 10 oz 1.25 oz/T	Pardee & Park, 1948; Dail & Hart, 1992; Callahan, Craig, and Bean, 1994

* New mineral for state of North Carolina

?? Samples were provided by a prospector and were reported to come from this area.

South Carolina

Mine Prospect/ Location by County	Telluride Mineral(s)	Associated Minerals	Geological Belt/ rock type(s)	Type of Deposit	Au Production	Reference(s)
Barite Hill / McCormick	Goldfieldite (?), Hessite, Sylvanite	Au, py, ba, Ag, ac, gn, cpy, cc, bn, cv, ten, atacamite(?), cosalite (?), sp, mb, Bi-, & Cu-selenides	CSB (Lincolnton-McCormick district) felsic metavolcaniclastics	Disseminated and veinlets	1,000,000 T at .04 oz/T	Back & Clark, 1993; Clark, and others, 1993; Gunter & Padgett, 1988
Brewer / Chesterfield	No identified minerals but high Te analyses of 10-33 ppm	Au, py, cpy, en, sp, tet, bn, tpz, il, gn, bn, cb, cv, Bi min.	CSB / felsic metavolcanic	Disseminated breccia pipe, placer	~ 225,000 oz	Bell & Larson, 1984; Butler and others, 1988
Haile / Lancaster	Altaite (?), Hessite (?), Krennerite (?), Sylvanite (?)	Au, py, sp, mb, po, asp, il, rt, tpz	CSB / felsic metavolcanics, volcaniclastics	Placer, disseminated, massive sulfide; vein	> 360,000 oz/ up to .55 oz/T	Bell & Larson, 1984; Kiff & Spence, 1988; Pardee & Park, 1948; Speer & Maddry, 1993
Hammett / Cherokee	Tetradymite (?)		KMB (?)			Lieber, 1858
Hull / York	Tetradymite	Au, py	KMB	Vein		Butler, 1964
Ridgeway / Fairfield	Hessite	Au, py, ac, sp, po, mb, ten	CSB / meta-volcaniclastics; metaturbidites	disseminated	57 MT at .032 oz/T	Gillon & Duckett, 1988; Duckett, Evans, and Gillon, 1988

Georgia

Mine Prospect/ Location by County	Telluride Mineral(s)	Associated Minerals	Geological Belt/ rock type(s)	Type of Deposit	Au Production	Reference(s)
Battle Branch / Lumpkin	Tetradymite (?)	Au, po, py, gn, cpy, mc, mt, il, ankerite, tr	Dahlonega (EBR) silicified mica schist; marble	Quartz lenses	~5,000 oz	German, 1989; Pardee & Park, 1948; Park & Wilson, 1936; Yeates and others, 1896
Boly Fields / Lumpkin	Tellurobismuthite originally Tetradymite	Au	Dahlonega (EBR)			Cook, 1973, 1978; Genth, 1868; Jackson, 1863
Pascoe / Cherokee	Tellurobismuthite originally called Tetradymite		Dahlonega (?)			Cook, 1973, 1994; Genth, 1868
Dahlonega (Consolidated)/ Lumpkin	Calaverite, Petzite, Sylvanite	Au, py, cpy	Dahlonega (EBR) biotite schist, iron formation, quartz, feldspathic gneiss, sericite schist and amphibolite	Thin, sheeted quartz veins in felsic dikes		Albino, 1990; German, 1994; Pardee & Park, 1948
Drake mine (?)/ Near Van Wost/ Polk	Tellurobismuthite (?) originally Tetradymite (?)					Cook, 1973, 1994; Little, 1875; Polk Shepard, 1859
Parks / McDuffie	Altaite	Au, py, gn, sp, cpy, supergene minerals, cv, pyromorphite, ank, ba, cc, tr-Ag	CSB	Vein	~3,600 oz $7.33/T	Callahan, Craig, and Bean, 1994; Pardee & Park, 1948; German, 1994
Royal Vindicator (Hollins, Holland, Camille, Royal) / Haralson	Altaite, Rucklidgeite*	Au, py, cpy, ga, sp, asp, stb, Cu, cc	felsic metavolcanics	-placer siliceous schist, with quartz veining	placer~40,000 oz ~100,000 penny weights	Paris, 1990; Callahan, Craig, and Bean, 1994
No mine name / Spalding	Tetradymite		Southern Piedmont			Cook, 1978
Tallapoosa (Waldron)/ Haralson	Tetradymite	Au, cpy, sp, py, dol	Dahlonega (EBR)	massive sulfide		Cook, 1973

* New mineral for the state of Georgia.

Belt Abbreviations

CSB - Carolina Slate Belt
CB - Charlotte Belt
EBR - Eastern Blue Ridge
GPB - Gold Pyrite Belt
IP - Inner Piedmont
KMB - Kings Mountain Belt

Associated Mineral Abbreviations

ac - atacamite
Ag - silver, assumed electrum
ank - ankerite
asp - arsenopyrite
Au - gold or electrum
ba - barite
bn - bornite
cc - chalcocite
Cu - native copper
cv - covellite
cpr - cuprite
cpy - chalcopyrite
dg - digenite
en - enargite
gn - galena
il - ilmenite
mc - malachite
mb - molybdenite
mt - magnetite
po - pyrrhotite
py - pyrite
rt - rutile
sp - sphalerite
stb - stibnite
tpz - topaz
tr - tourmaline
ten - tennantite

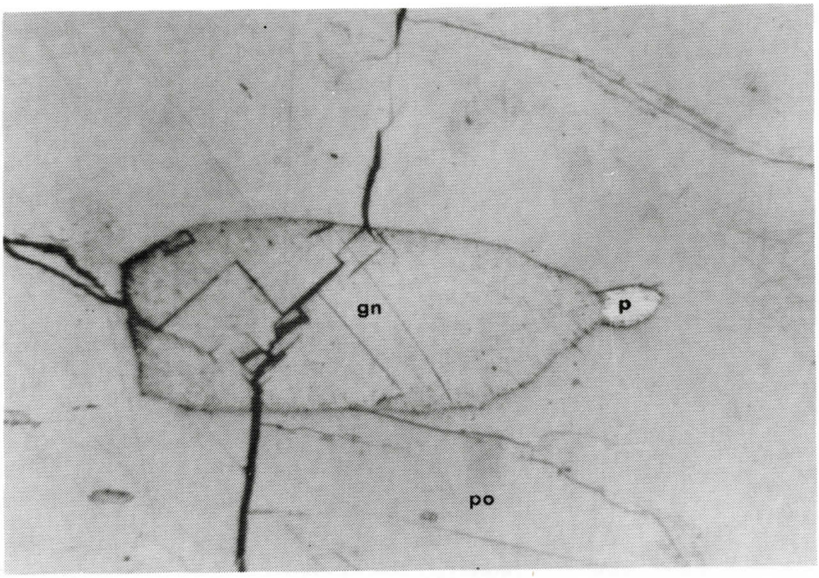

Figure 2. Photomicrograph of small grain of pilsenite (?) ($Bi4Te_3$) (p) at the end of a grain of galena (gn) set in a mass of pyrrhotite (po). Great Gossan Lead, Virginia. Width of field = 0.24 mm.

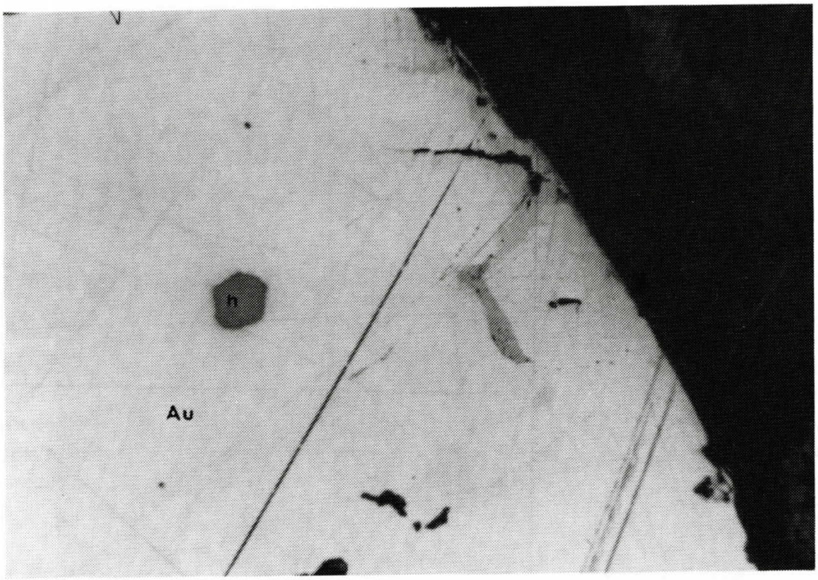

Figure 3. Photomicrograph of round grain of hessite (Ag_2Te) (h) in a gold nugget (Au) from North Carolina. The gold nugget contains 83.4 wt.% gold and 16.6 wt.% silver. Near the margin the slightly darker rim and the zone that extends into the nugget is virtually pure gold. Mount Pleasant, North Carolina; width of field = 0.6 mm.

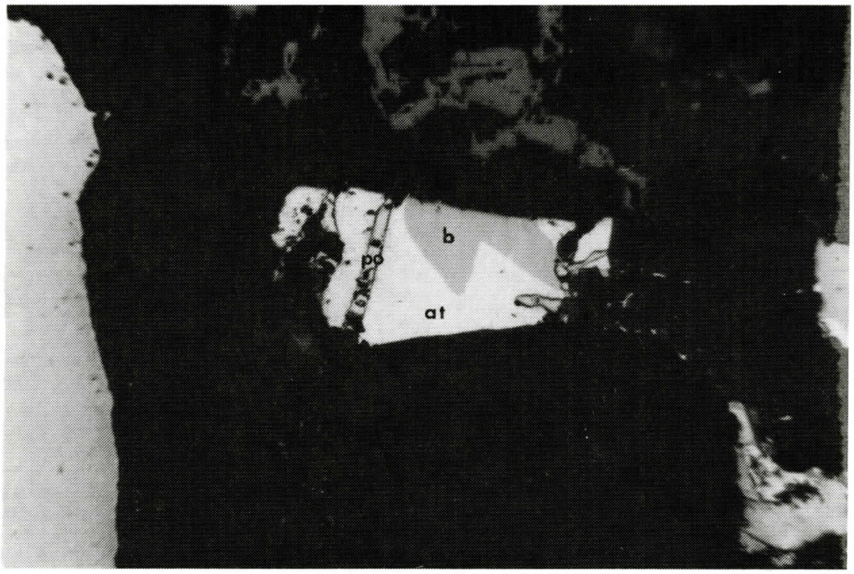

Figure 4. Photomicrograph of altaite (PbTe) (at) with boulangerite ($Pb_5Sb_4S_{11}$) (b) cut by a small veinlet of pyrrhotite (po). Kings Mountain, N.C.; field of view = 0.60 mm.

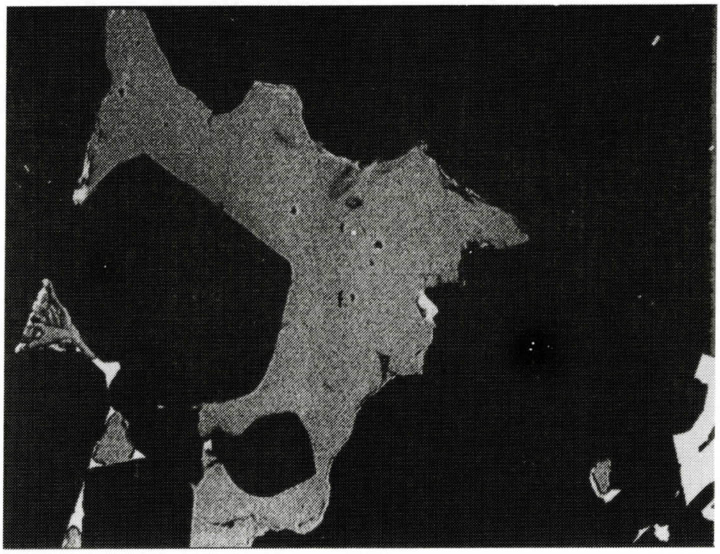

Figure 5. Back scattered electron (BSE) image of frohbergite (?) (f). Reynolds (Star) mine, N.C.; width of field = 0.43 mm.

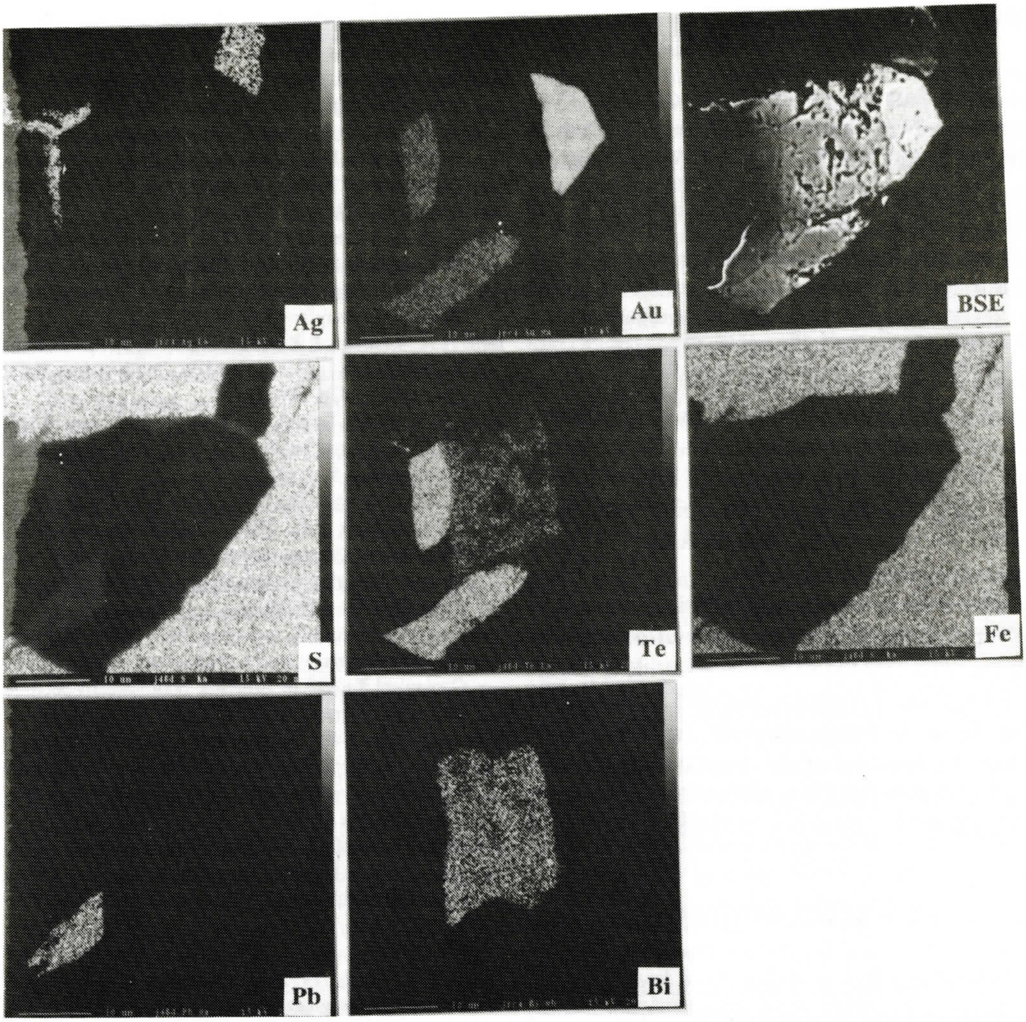

Figure 6. Back scattered electron (BSE) image and select element scans of a group of grains in a sample from the Royal Vindicator Deposit, Georgia. The BSE image appears much like an optical image, but results only from the scattering of electrons by the grains. The distribution of the elements demonstrates that the minerals present include: a central core of pilsenite (?) (Bi_4Te_3), calaverite ($AuTe_2$) in the south and west, galena (PbS) in the southwest, acanthite (Ag_2S) in the northeast, and gold (Au) in the northeast all in a matrix of pyrite (FeS_2).

and all but those reported for the Reynolds (Star) mine and the Daniels mine were determined by the authors. Analyses for native tellurium from the Daniels mine in Charlotte County, Virginia were provided by Neil Johnson (1994). The most unique telluride mineralogy, so far observed for any location in the southeast, is from the Reynolds (Star) mine, which has tellurium assays as high as 2.24% (Kiff, 1966). Those minerals reported from the Reynolds (Star) mine are based on microprobe analyses of mineral separates listed in a previously unpublished consulting report by Stephens (1982). The authors have confirmed the presence of a Au-Ag telluride, a Au-telluride, an Sb-telluride, altaite, coloradoite and frohbergite (?) from this deposit.

CONCLUSIONS

Telluride minerals have been identified from a total of 36 locations in the southeastern United States. Virginia has 10, North Carolina has 14, and South Carolina and Georgia each have 6 occurrences. Tetradymite was originally reported in the literature as the most common telluride, but many of the early reported (1800's) analyses have been shown by Cook (1973, 1994) to be other Bi-Te minerals. Tellurides in the southeast occur most commonly in gold-vein deposits and also in massive sulfides, disseminated lodes, and placers. These minerals occur in a variety of geologic belts of different ages and are most commonly associated with volcanics and volcaniclastics or their metamorphosed equivalents.

The wide distribution of telluride minerals in a variety of gold and massive sulfide deposits in the southeast indicates that telluride mineralization is quite common. Because all but one of the Te occurrences noted are associated with gold deposits, tellurium may be useful as a pathfinder element in geochemical exploration programs for gold in the southeast.

ACKNOWLEDGMENTS

We would like to thank the following individuals and one company for providing us with polished thin sections, specimens and an internal consulting report that made this compilation possible: W. C. Bean, Dennis LaPoint, Jerry German, Travis Paris, and Piedmont Mining Company. We would like to thank Neil Johnson for providing previously unpublished analyses for the Daniels mine. We sincerely appreciate the help that Marjorie McKinney provided in drafting and preparing the figure and table for publication. We would also like to acknowledge the contributions of J.W. Miller, N.E. Johnson, R.B. Cook, and B. Geller who edited the manuscript.

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APPENDIX

Electron microprobe analyses of minerals identified in this study.

Virginia

Long Island Creek

Single Nugget (Harvard Museum Sample 1345) (GPB)

Mineral Name	Formula	Weight Percent					
		Bi	S	Pb	Ag	Te	Σ
ALTAITE	PbTe		0.04	59.72	0.05	38.26	98.07
RUCKLIDGEITE	$(Bi,Pb)_3Te_4$	36.95	0.01	16.18	0.19	45.74	99.07

Iron Ridge Mine

(Bumbarger Pit) (Great Gossan Lead)

Mineral Name	Formula	Weight Percent							
		Bi	Sb	S	Pb	Au	Ag	Te	Σ
HESSITE **(average 3 grains)**	Ag_2Te	0.32	0.43	0.38	0.84		63.67	35.22	100.86
HEDLEYITE ? **(average 3 pts)**	$Bi_5Bi_2Te_3$	80.56	0.28	0.48	2.33	0.02	0.03	17.58	101.28
PILSENITE ? **(average 2 grains)**	Bi_4Te_3	69.78	0.38	0.14	1.4		0.03	27.56	99.29

Other minerals of interest might include Native Bi (?) and other Bi,Pb-telluride minerals(?).

Daniels Mine

(Virgilina District) (CSB)

Mineral Name	Formula	Weight Percent							
		Bi	Sb	S	Pb	Au	Ag	Te	Σ
HESSITE **(average 3 points)**	Ag_2Te	0.03		0.105	0.020		62.70	36.74	99.60
NATIVE TELLURIUM	Te			0.36			0.01	99.28	99.65

Microprobe data provided by N.E. Johnson, 1994

North Carolina

Mt. Pleasant Area

(Placer nuggets from Prospector) (CSB)

Mineral Name	Formula	Weight Percent							
		Bi	S	Hg	Pb	Au	Ag	Te	Σ
ALTAITE	PbTe	2.51	0.12		55.77		3.22	38.22	99.84
CALAVERITE(?)	$(AuAg)Te_2$	(from SEM-EDAX analysis, not confirmed by probe yet)							
COLORADOITE	HgTe			61.80			0.16	38.70	100.66
HESSITE	Ag_2Te		0.02	0.17	0.08		62.13	36.71	99.11
PETZITE	Ag_3AuTe_2	0.08		0.22		25.40	40.00	33.46	99.16

Russell Mine

(CSB)

Mineral Name	Formula	Weight Percent						
		Sb	S	Pb	Au	Ag	Te	Σ
HESSITE	Ag_2Te	0.54	0.09	0.09	0.20	64.63	35.43	100.98
PETZITE **(average of 4 pts)**	Ag_3AuTe_2	0.23	0.02	0.11	25.02	43.48	31.18	100.04

Star (Reynolds) Mine

(CSB)

Initial reports of the following minerals provided by Piedmont Mining from a 1982 consulting report by Mr. J.D. Stephens for Kennecott Minerals Company by microscopic and electron beam microprobe studies.

ALTAITE	PbTe
CALAVERITE	$(Au,Ag)Te_2$
COLORADOITE	HgTe
FROHBERGITE(?)	$FeTe_2$
KRENNERITE	$Au_{0.8}Ag_{0.2}Te_2$
SYLVANITE	$(Au,Ag)_2Te_4$

Other minerals from the Star Mine identified in the same report were gold, native iron, magnetite, pyrite, chalcopyrite and sphalerite. Preliminary EDAX analysis at VPI has identified altaite, coloradoite, frohbergite, a AuAgTe mineral, a AuTe mineral, and a Sb-Te mineral (tellurantimony ?) from a polished section made from Star Mine samples provided by John Maddry of Piedmont Mining.

Georgia

Parks Mine

(CSB)

Mineral Name	Formula	Weight Percent					
		Bi	S	Pb	Ag	Te	Σ
ALTAITE **(average 3 points)**	PbTe	0.18	0.98	63.78	0.11	36.11	101.16

Royal Vindicator

(Carroll Co. Gold Belt)

Mineral Name	Formula	Weight Percent						
		Bi	S	Pb	Au	Ag	Te	Σ
ALTAITE **(average 2 pts)**	PbTe	0.17	0.03	60.27		0.06	38.00	98.53
CALAVERITE(?) **(1 pt)**	$(AuAg)Te_2$	0.54	0.05		38.87	1.31	57.11	97.88
RUCKLIDGEITE	$(Bi,Pb)_3Te_4$	36.78	0.26	16.20		0.47	45.07	98.78
TETRADYMITE **(average 2 pts)**	Bi_2Te_2S	58.14	4.84	1.49		0.17	35.50	100.14

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PALYNOSTRATIGRAPHY AND ENVIRONMENT OF DEPOSITION OF BROWN COAL FROM BENEATH THE TRAIL RIDGE ORE BODY, FLORIDA

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ABSTRACT

A 28.5 cm core of brown coal (dense, diagenetically mature peat) identified as H2 35 was recovered from a rotary jet drill hole on the Trail Ridge Ore Body in north central Florida. The brown coal was described megascopically, with such features as charcoal and leaf compressions being noted. The core was also sampled at 28 levels and analyzed for its fossil pollen content. Palynological evaluation indicates that the brown coal was produced by species of plants which still live in swamps of the southeastern United States. Furthermore, the plant communities which produced the sediment changed as time passed, varying from open shrub swamp with abundant herbaceous plants, to rather dense vegetation composed largely of woody plants. Abundant charcoal layers and the coincidental appearance of herbaceous species suggest close comparison of some portions of the H2 35 core with modern "prairies", or marshes of the Okefenokee Swamp.

INTRODUCTION

Samples of organic sediment were recovered from a drill hole in north central Florida in 1988. The hole was drilled in association with heavy mineral sand production, and was located on the Trail Ridge Ore Body in Clay County, Florida (Fig. 1). The core site, located a 61 m (200 feet) above sea level was initially bored using an auger; the rotary drilling process was used subsequently and bentonite drilling fluid was circulated in the borehole to stabilize the sides and flush cuttings. The samples which were analyzed for this project were obtained with a standard 1.4 inch I.D. split-tube (split-spoon) sampler. The principle sediment encountered in the hole was light to dark brown sand, but at about 10.1 m below the surface, dark woody sediment was encountered. The core sample discussed in this paper, identified as H2 35, was collected with a split-spoon, and was recovered from the drill hole intact. Because previous work by Rich (1985) had shown that such organic sediments contain well-preserved freshwater swamp/marsh pollen assemblages, the dark woody sediment was prepared for palynological analysis.

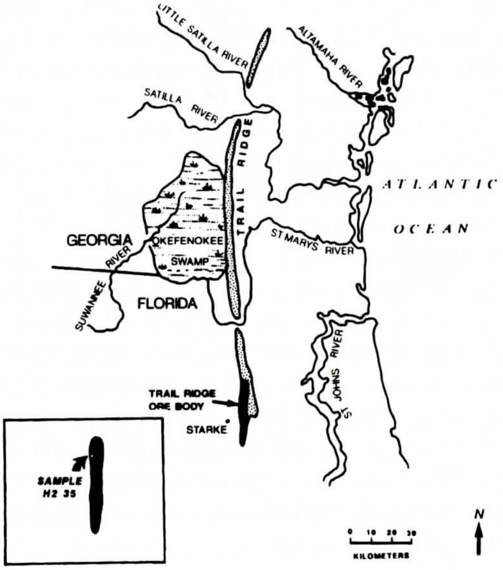

Figure 1. Location of the Trail Ridge Ore Body and the H2 35 core site.

The Trail Ridge Ore Body is one of a number of sand accumulations in the southeastern United States which have been intensively studied for their economic potential. Pirkle and Yoho (1970) present a detailed description of the Trail Ridge heavy-mineral sand deposit, and identify it as a part of the topographic feature known as Trail Ridge. The age of Trail Ridge has been a matter of conjecture for many years, and has not yet been determined with any precision. Pirkle and Yoho (1970), Pirkle and others (1977), F. L. Pirkle (1984), and Force and Rich (1989) each describe various attributes of Trail Ridge sediments and suggest that they probably accumulated during the Pleistocene; Pirkle and Czel (1983) and Rich (1985) discuss paleontological remains which further constrain the age of Trail Ridge and, therefore, the time of deposition of the Trail Ridge ore body sands. Their work suggests that the sand body is no older than Pliocene, though it could be Pleistocene. At present no biostratigraphic or radiometric evidence exits, however, which can be used to prove that Trail Ridge is either of Early Pleistocene or Late Pliocene age. As can be seen in the results of the H2 35 analyses, even our most recent set of palynological data fail to provide clear proof of the age of Trail Ridge.

CHARACTERISTICS OF THE H2 35 SAMPLE

The sample identified as H2 35 consisted of three cylindrical pieces of firm, dusky brown and moderate brown (5YR 2/2 and 5YR 3/4) organic sediment. Both the color of the sediment and its firmness (it could be cut with a knife, but with difficulty) lead to its identity as a brown coal. The fact that brown coal was encountered in the hole was not surprising because such occurrences are commonplace beneath Trail Ridge. Rich and others (1978) described the petrographic characteristics of brown coal from a site near Starke, Florida, and concluded that, based upon a variety of optical characteristics, the Trail Ridge sediment is indeed brown coal. The three sections of the H2 35 brown coal totalled 28.5 cm of sediment. The core sample was described and subsampled at 1 cm increments (producing 28 small samples) in order that a depositional sequence of plant communities and environments of deposition could be described.

Most of the brown coal consisted of dense, dark brown, laminated sediment. The lower 5 cm bore minute (1mm) laminations of white sand intercalated with organic detritus (see left column of Fig. 5). Compressed plant fragments were abundant and clear on the bedding planes of many of the 1cm core segments. Many of the compressions were those of small sclerophyllous (i.e. thick or leathery) leaves, and those frequently had pitted, shiny upper surfaces; numerous narrow, strap-like leaves suggestive of grasses or sedges were also present on some of the bedding planes; none of the leaf compressions have been identified yet. At about 17 cm below the top of the brown coal sample, layers of charcoal were present and were interlayered with the laminations of sand and layers of the grass-like leaves.

PROCESSING TECHNIQUE

Approximately 1 gram of sediment was taken from each 1cm interval of the H2 35 core. Each 1-gram sample was boiled in 10% KOH for five minutes. In each case the samples produced very dark supernatant fluids and abundant insoluble organic residues. After thorough washing to remove the soluble organic fractions, processing was terminated and the residues were mixed with a 50:50 blend of water and glycerine jelly. Two microscope slides were prepared for each of the 28 samples and a minimum of 200 identifiable grains was counted for each sample. Counts were made by observing the slides with a Jena research photomicroscope, equipped with a mechanical stage which permitted X-Y movement. Pollen data were graphed in histogram style and are presented here as Figures 2 and 3.

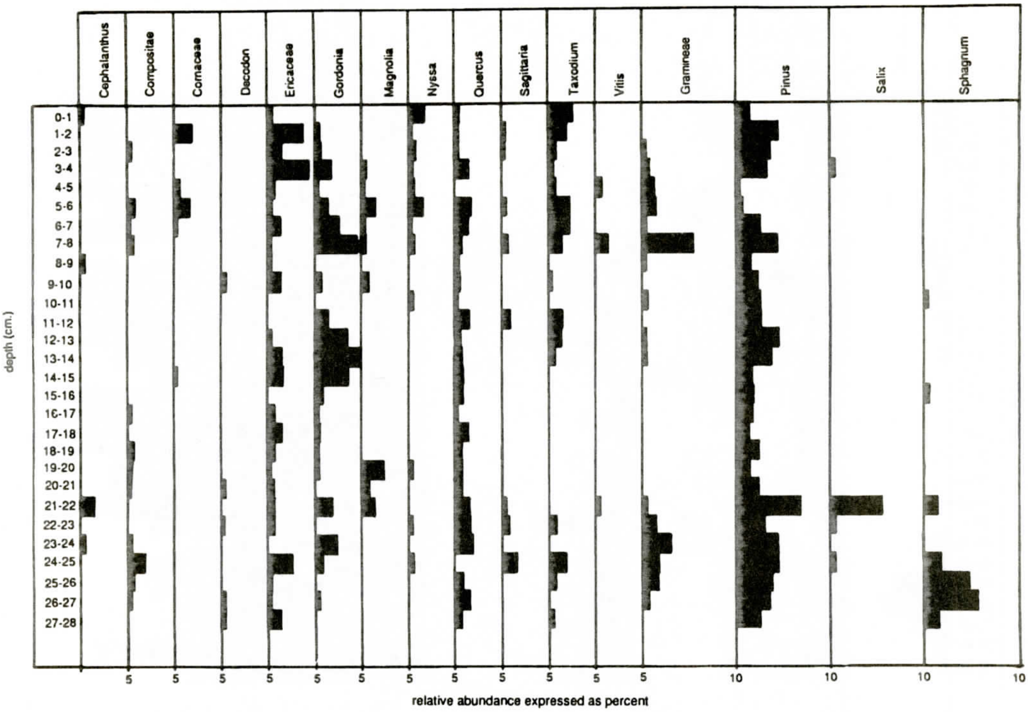

Figure 2. Relative abundances of selected taxa from Core H2 35, expressed as percent of total pollen and spores, 5 - 10% range.

RESULTS OF THE ANALYSES

Figures 2 and 3 illustrate the abundances of spores and pollen relative to the depth from which the 1cm samples came. Figure 4 illustrates selected pollen of herbaceous plants, shrubs, and trees which were found in the core. Core H2 35 can be subdivided into three zones palynologically, as follows:

0 - 8 cm - Gordonia-Taxodium - grass zone
8 - 21 cm - Gordonia-shrub zone
21 - 28 cm - Cyrilla- Sphagnum- grass-sedge zone

The Gramineae (grasses), the Compositae (asters and relatives), and the Cyperaceae (sedges) all have bimodal distributions within the core, and their peaks of abundance are mutually coincidental. Thus, they constitute parts of two assemblages, one at the base of the core and one near the top. Differences in those two assemblages include significantly different amounts of the shrub genus Cyrilla (ti-ti), which diminishes upward in the core. Salix (willow) is present in the lower assemblage, and although it is not persistent and abundant, it does display a distinct peak at 21-22 cm (Fig. 2). The same is true of the moss Sphagnum, which is unusually abundant (relative to most Trail Ridge samples, e.g. Rich, 1985)) at the very bottom of the core, then diminishes rapidly upward. There is a noticeable increase in the amount of Ericaceae (heath) pollen in the uppermost assemblage. Heath pollen is almost never abundant in modern peats from the Southeast, unless the peat has been produced by a community of heath shrubs (Cohen, 1975; Rich, 1979). Amounts approaching 5%, such as is the case in the uppermost portion of the H2 35 core are, therefore, unusual.

The middle portion of core H2 35 is where the entomophilous (insect pollinated) tree Gordonia (loblolly bay) displays its greatest pollen abundance (5%, an unusually high percentage

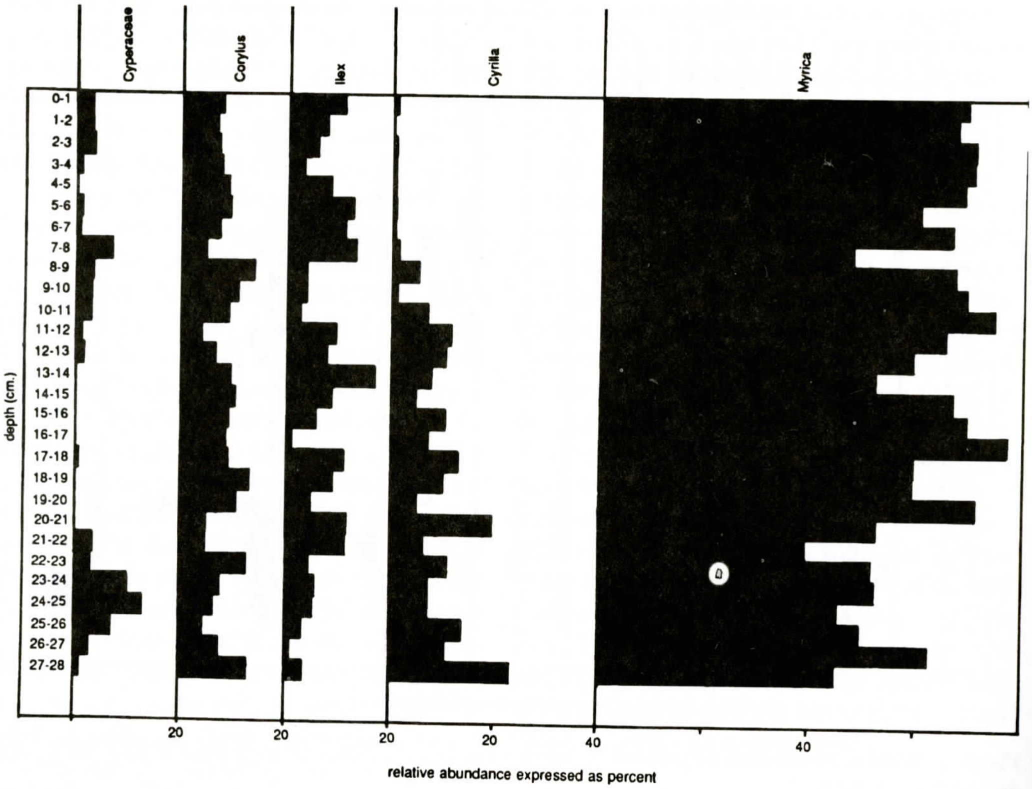

Figure 3. Relative abundances of selected taxa from Core H2 35, expressed as percent of total pollen and spores, 20 - 80% range.

for peats from the Southeast; see Rich, 1979, Fearn and Cohen, 1984, and Fair-Page and Cohen, 1990 for analytical results which support this). Cyrilla pollen is also abundant and persistent in the middle portion of the core. The appearance of both Gordonia and Cyrilla pollen between 8 and 21 cm is consistent with the fact that these two plants commonly grow together in shrub-dominated swamps in the southeastern U.S. today.

INTERPRETATION OF THE DEPOSITIONAL SEQUENCE

In a general sense the sequence of zones in core H2 35 reflects a change in plant communities from a Cyrilla shrub swamp with abundant Sphagnum and grasses or sedges and a closed canopy of branches, to a shrub swamp, and thereafter to a tree/shrub swamp with an open canopy and abundant grasses and sedges. The pollen of one genus which is common throughout the sequence is Myrica, the wax myrtle. This shrubby plant must have been present in large numbers regardless of how other species appeared and vanished. However Myrica may have responded to environmental changes, it is pretty clear that the other taxa tended to appear, persist, then vanish, sometimes to reappear later. Evidence of a successional sequence is suggested to exist here, with the succession beginning at the bottom of the stratigraphic section with grasses, sedges, Sphagnum, composites, and Cyrilla occupying the site along with Myrica. This would have been an open, sunlit, freshwater shrub/marsh community which existed once wetland conditions were established at the site of deposition. This community of plants is actually very common in

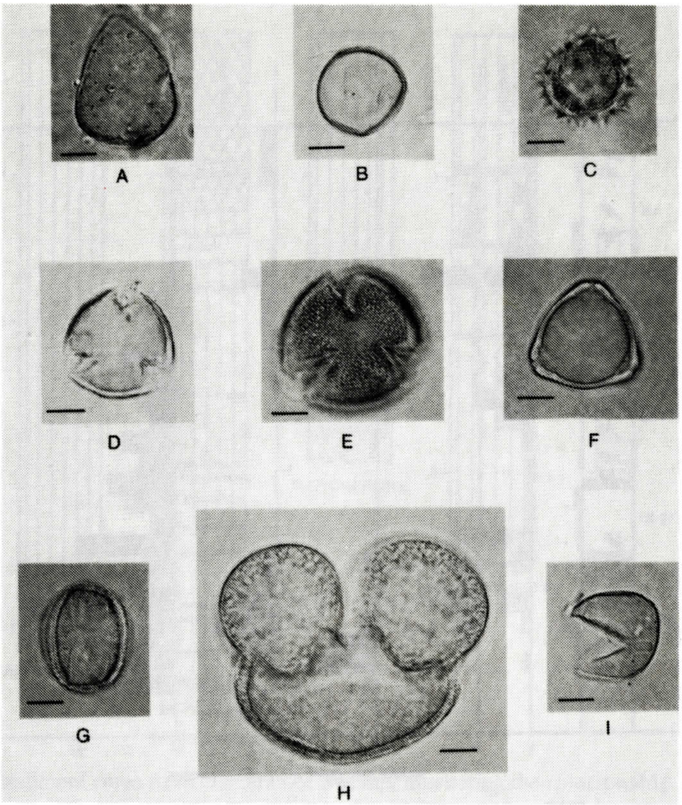

Figure 4. Selected pollen from the H2 35 site. A) Cyperaceae, B) Gramineae, C) Compositae, D) Cyrilla, E) Gordonia, F) Myrica, G) Quercus, H) Pinus, I) Taxodium. All photographs are the same magnification, bars represent 10 microns.

southern Georgia and northern Florida and may be seen growing almost anywhere on the Coastal Plain where there is abundant sunshine, few trees, very moist soil, and plenty of rain. This community is, furthermore, adapted to survive where fires periodically burn through an area (see Izlar, 1984 for related detail). Above-ground parts of the shrubs may be destroyed by fire, but many of the plants are capable of regenerating stems and branches and may repopulate a burned area fairly quickly. Burning in the early stages of development of this sedimentary sequence might have enhanced the survival of the shrubs at the expense of shade-generating trees. Cypert (1961) made careful note of the effects of fires that burned areas in the Okefenokee Swamp in 1954 and 1955 and, among his observations, he determined that Cyrilla and Ilex both had a capability to withstand burning and reestablish themselves after rather severe burning.

As the shrubs of the early community proliferated and the spaces between them closed, the herbaceous community was gradually eliminated. Judging from the steady decline of Cyrilla pollen between 21 and 8 cm, it, too, was either shaded out or disappeared from the site due to some other environmental change. Both Ilex and Myrica persist, and may simply have out-competed Cyrilla. The tree Gordonia and various shrubs of the Ericaceae moved into the site at the time the 15 cm level accumulated. These seem to have ushered in further changes as the wetland gradually matured. Taxodium (cypress) and Nyssa (black gum or tupelo) pollen appear near the top of the core, and show that swamp forest vegetation eventually inhabited the area. Their pollen are not

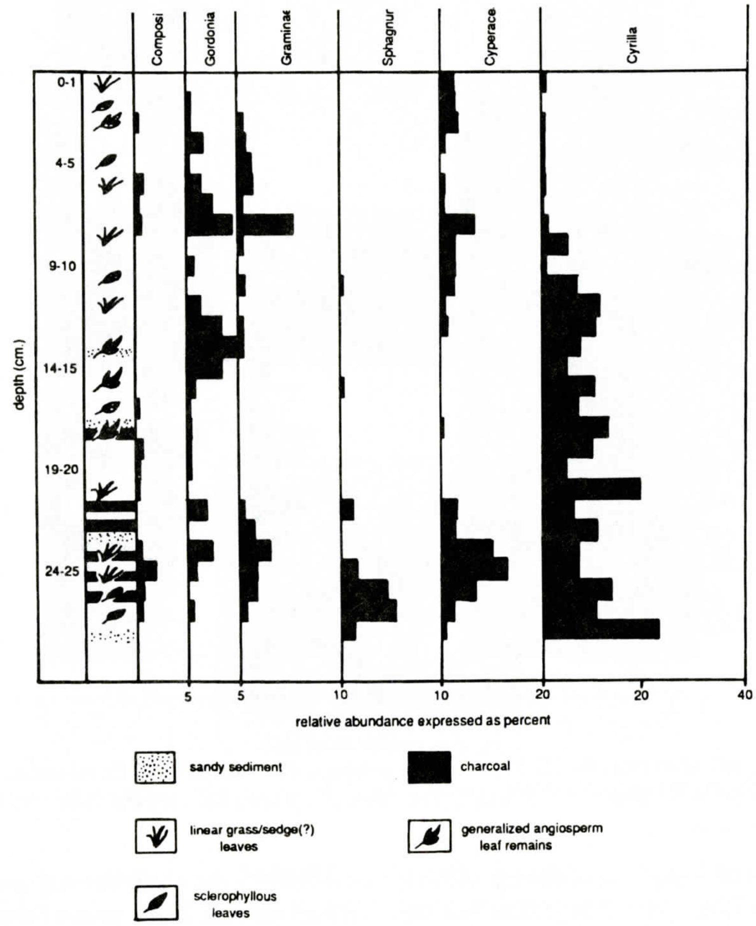

Figure 5. Megascopic and microscopic characteristics of Core H2 35 plotted against relative abundances of selected pollen and spores. Note change of scale in last two columns on right.

abundant enough anywhere in the core, however, to suggest that cypress-tupelo forest stood at the site where the H2 35 core was collected. Rather, a mixture of Myrica shrubs and a variety of trees seem to have provided a rather open, though probably shady swamp. Shade-tolerant herbaceous species (the sedge Eleocharis, for example) began growing in the area beneath the taller woody plants and remained there to the end of peat deposition.

Megascopic and microscopic sediment characteristics have been plotted adjacent to selected pollen/spore histograms in Figure 5. Vertical changes in sediment composition match very closely with changes in relative abundances among the key pollen/spore types. For example, between 21-28 cm there are prominent charcoal bands and quite a bit of sand. Common megascopic plant remains include linear, strap-shaped leaf compressions believed to be grass and/or sedge remains. This type of association, i.e., grasses and sedges and a fire-prone habitat is commonplace among wetlands. Numerous sediment cores from Okefenokee Swamp illustrate this point (Fig. 6); charcoal-bearing herbaceous peat is the dominant type of sediment one finds low in the stratigraphic section in the Okefenokee peat

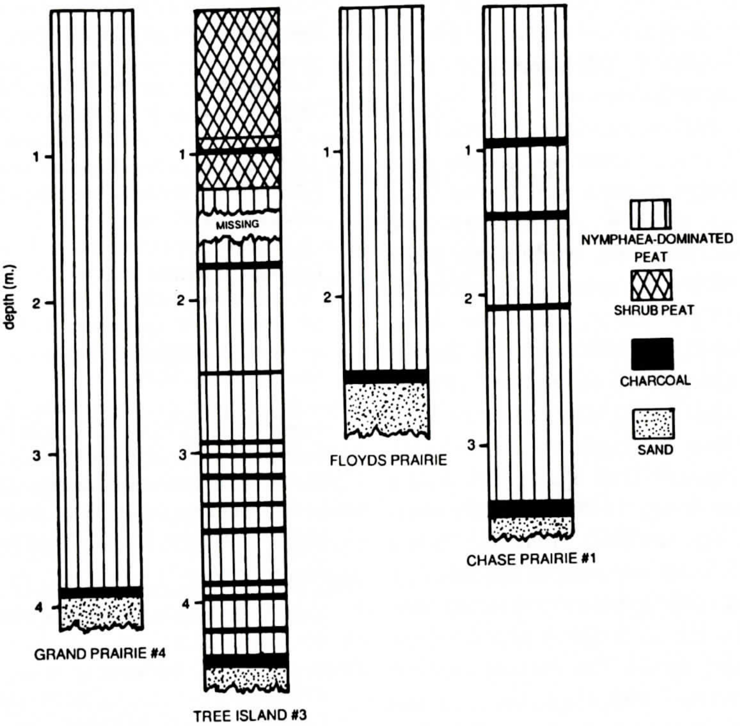

Figure 6. Selected sediment cores from Okefenokee Swamp, illustrating the relationship between herbaceous peat and abundant charcoal (Grand Prairie, Tree Island #3, and Floyds Prairie cores from Spackman and others, 1974, Chase Prairie core from Rich, 1979).

deposit. It is also typical of the open marshy "prairies" of the swamp. Between 12 and 21 cm depth, the charcoal layers decrease in number, though there are still two sandy horizons, and the linear strap-shaped leaves vanish. Angiosperm leaves, probably derived from broad-leaved trees, and thick, sclerophyllous leaves which might have fallen from shrubs are common in this interval. Between 0 and 12 cm there are no charcoal beds and no sand, and the grass/sedge leaves become more common again; they are mixed with the broad-leaved and sclerophyllous plant fragments, indicating mixed vegetation types in a wetland which supported relatively high diversity.

THE DEMISE OF THE H2 35 WETLAND

Although it is probably impossible to get an absolute age for the H2 35 sample (similar deposits exhibited no radiocarbon activity) it seems likely that the wetland must have existed for several hundred years. The density of the brown coal and its diagenetic maturity suggest that considerable compaction took place within the sediment. The 28 cm of brown coal could easily have been produced from three or four times as much peat. If we conservatively estimate a compaction ratio of three to one, then there would have been 84 cm of peat at the time accumulation ceased. Although average accumulation rates of peat can vary tremendously, depending upon climate, nature of the vegetation, and level of microbial activity, useful estimates can be made in an environment which is probably our best analogue for the Trail Ridge wetlands, i.e., the Okefenokee Swamp. The rate of accumulation in the Okefenokee Swamp (.6 mm per year for the Tree Island #3 core of Spackman and others,

1974) suggests that 84 cm of peat might have developed over as much as 1400 years. The H2 35 wetland was clearly well-established, so its demise is of scientific interest.

The brown coal is overlain by nearly 10 meters of sand, as mentioned earlier. The geology of Trail Ridge is quite well known (e.g., Pirkle and Yoho, 1970; W. A. Pirkle, 1972). It is generally accepted that, while some stratigraphic units within the ridge may have originated as shoreline sands under the direct influence of waves and ocean currents, there is a substantial amount of eolian sand (Pirkle, 1975). Force and Rich (1989) illustrated the relationship which the brown coal producing communities beneath Trail Ridge had with a system of eolian dunes which eventually overran the Trail Ridge wetlands. Since H2 35 is a part of the Trail Ridge deposits, as described by Force and Rich (1989), there is the strong suggestion that the H2 35 wetland was similarly buried by moving dunes. The wetland died out as it was covered by a thick blanket of sand, and wetland conditions were never reestablished.

ACKNOWLEDGMENTS

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GEOLOGY OF THE SUBSURFACE DAYS CHAPEL OIL AND GAS FIELD IN THE MISSISSIPPIAN MONTEAGLE LIMESTONE, EAGAN QUADRANGLE, NORTHWESTERN CLAIBORNE COUNTY, TENNESSEE

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ABSTRACT

Gamma, Bulk Density and Porosity geophysical logs of producing oil and gas wells from the subsurface Mississippian Monteagle Limestone within the Days Chapel Field on the Eagan quadrangle located in the Pine Mountain thrust block in Claiborne County, Tennessee, enabled preparation of a structure contour map atop the Monteagle; an isopach map of the Monteagle; and mapping of the stratigraphic distribution of porous zones within the Monteagle. The structure contour map shows asymmetric anticlines and synclines that trend northeast-southwest which were possibly formed during the northwestern tectonic transport of the Pine Mountain thrust block. The isopach map indicates portions of northeast-southwest-trending mounds that are interpreted as tidal bars (Handford, 1978). Porous zone cross sections in the Days Chapel Field document an ubiquitous major porous zone near the base of the Monteagle. Other porous zones above this major zone show laterally discontinous distribution at several stratigraphic levels.

INTRODUCTION

Figure 1 shows the location of the Eagan quadrangle in Claiborne County, northeastern Tennessee. Figure 2 locates the Eagan quadrangle on the Pine Mountain thrust block.

The purpose of this paper is to examine the occurrence of oil and gas in the Days Chapel Field Monteagle limestone (Mississippian) and offer an explanation of the origin of its porosity.

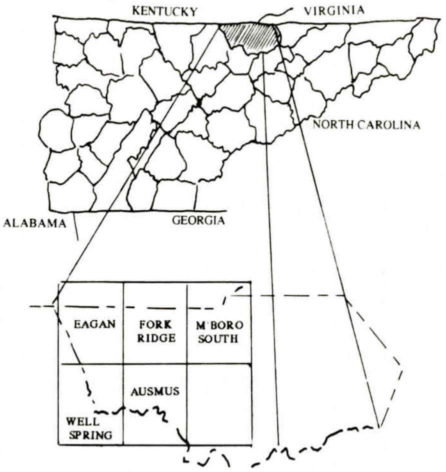

Figure 1. Location of Claiborne County, northeastern Tennessee.

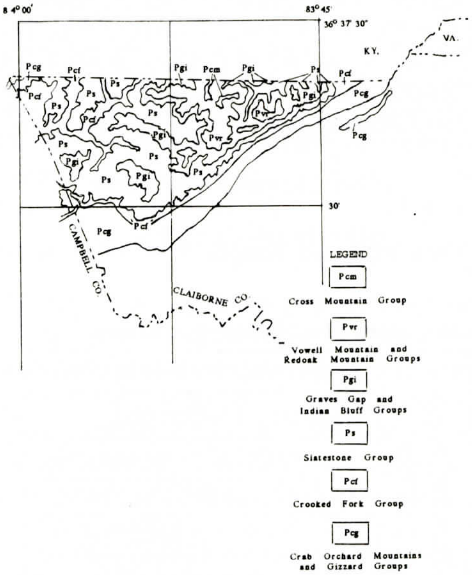

Figure 2. Eagan Quadrangle situated on Pine Mountain thrust block.

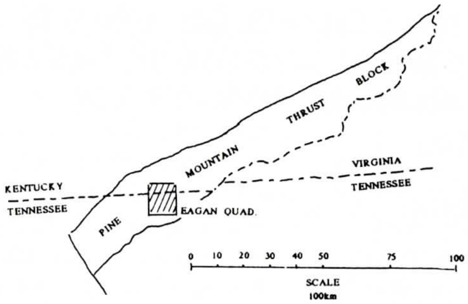

Figure 3. Pennsylvanian stratigraphic sequence exposed on surface, Eagan Quadrangle.

STRATIGRAPHY

Data taken from the Pennsylvanian Folio by C.W. Wilson and others (1956) is presented on Figure 2which shows a thick exposure of Pennsylvanian rocks on the Eagan quadrangle (northwestern Claiborne County). Table 1 lists the underlying Mississippian formations in ascending order.

STRUCTURE

As indicated, Figure 3, rocks of the Pine Mountain thrust block have been moved from their original site of deposition by as much as 30 kilometers to the northwest. Further, additional data from C. W. Wilson and others (1956), (Figure 4) shows subsurface Habersham and Fonde structural basins as well as an anticlinal structure in the southwestern part of the Eagan quadrangle.

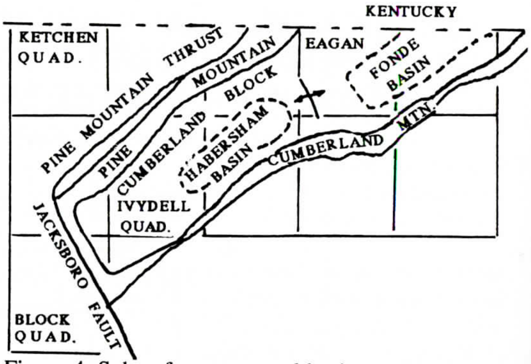

Figure 4. Subsurface structural basins and anticlinal structure on Pine Mountain thrust block.

Days Chapel Field Maps

Townships and Ranges of the Tennessee Carter Coordinate System (Eagan quadrangle) are presented on Figure 5. Information on the configuration of the Days Chapel Field plus well permit numbers (example, 7439) and the nature of production from the wells (oil, gas, or oil and gas combination) was obtained from the Tennessee Division of Geology oil and gas well location map (Eagan Quadrangle) which was posted in 1988. Geophysical well logs (as of 1988), composed of gamma, bulk density and porosity logs, from the Days Chapel Field were purchased from the Appalachian Well Log Service of Midland, Texas.

Table 1. Subsurface Mississippian System

MISSISSIPPIAN SYSTEM	PENNINGTON FORMATION
	BANGOR LIMESTONE
	HARTSELLE FORMATION
	MONTEAGLE LIMESTONE
	ST. LOUIS LIMESTONE
	WARSAW FORMATION
	FORT PAYNE FORMATION

Figure 6 is a map of the Days Chapel Field showing well locations and well permit numbers plus the nature of production. In addition, cross-sections, or panels, used to mark Monteagle tops and bottoms and map the stratigraphic position of porous zones are marked A through N.

Geophysical Log Interpretation

Gamma, bulk density and porosity graphic logs are the major tools used to determine "tops," or contacts, as well as the stratigraphic positions of porous zones in subsurface formations. Gamma graphs are situated on the left side of a geophysical log and serve to distinguish shale units from sandstone or limestone units. A shift of the gamma graph to the right marks increasing gamma ray activity characteristic of shale units. In this case, the gamma log is used to distinguish the upper contact (top) of the Monteagle Limestone (Table 1) from the

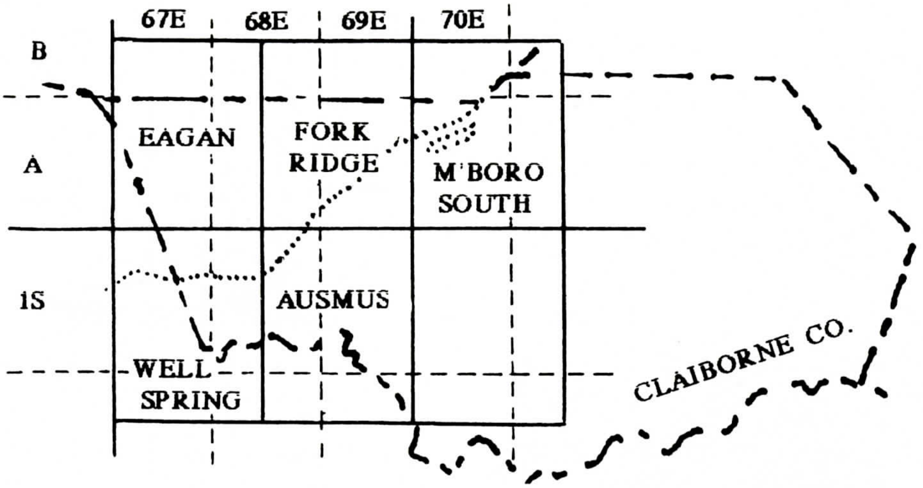

Figure 5. Townships and ranges, Tennessee Carter Coordinate System.

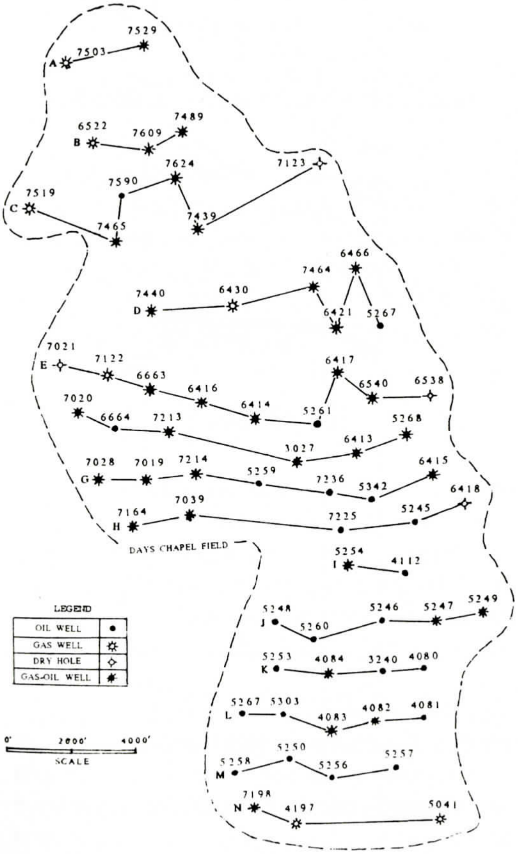

Figure 6. Well locations and well permit numbers plus nature of production, Days Chapel Field, Eagan Quadrangle.

overlying shale-rich Hartselle Formation (Table 1).

Bulk density graphs (logs) are located on the right side of a geophysical log. Bulk density graphs that are displaced to the right, record increasing rock density and conversely, to the left, decreasing rock density. The bottom contact of the Monteagle with the underlying St. Louis Limestone (Table 1) has been selected where the chert-rich upper portion of the St. Louis displaces the bulk density graph to the right.

Porosity logs are also located on the right side of a geophysical log and are associated with the bulk density logs. Graphs of percent porosity are recorded as a shift to the left in two percent increments.

Structure Contour Map

Figure 7 is a structure contour map showing the configuration of the upper surface of the subsurface Monteagle Limestone. The lower numbers are closest to the surface and the higher numbers are farthest from the surface (deeper). The top of the Monteagle is seen as a "corrugated" surface of asymmetrical anticlines and synclines.

Earlier it was noted on Figure 4 that a northwest-southeast-trending anticlinal structure is situated in the southwestern part of the Eagan

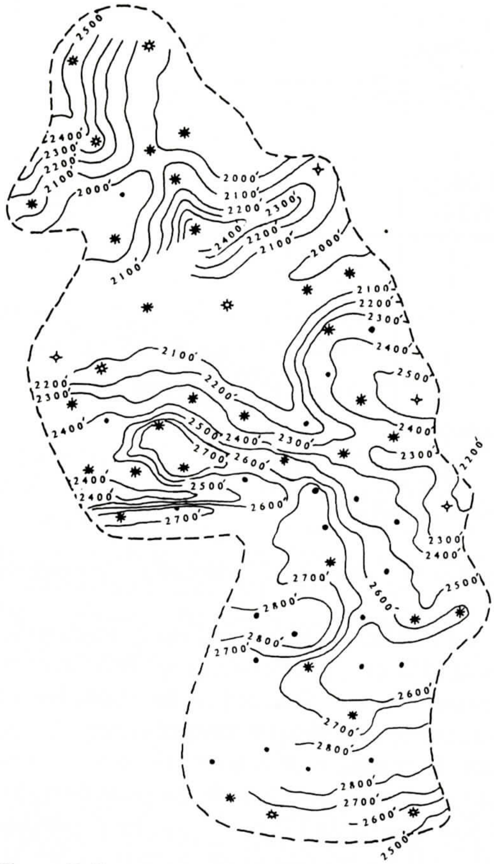

Figure 7. Structure contour map of upper surface of subsurface Mississippian Monteagle Limestone.

quadrangle, and it was thought that perhaps this anticline controlled oil and gas distribution in the Days Chapel Field. However, study of Figure 7 reveals no northwest-southeast-trending anticlinal feature, and inasmuch as the Monteagle is folded along generally northeast-southwest-trending axes, it may be suggested that northwestward displacement of the Pine Mountain Thrust Block may have influenced configuration of the upper surface of the Monteagle.

Initially, it was thought that the Days Chapel Field would show a classic gas and oil separation in an anticlinal fold. Nonetheless, after careful scrutiny of the Monteagle structure contour map and the location of wells yielding oil and gas respectively there seems little support for such a classic situation.

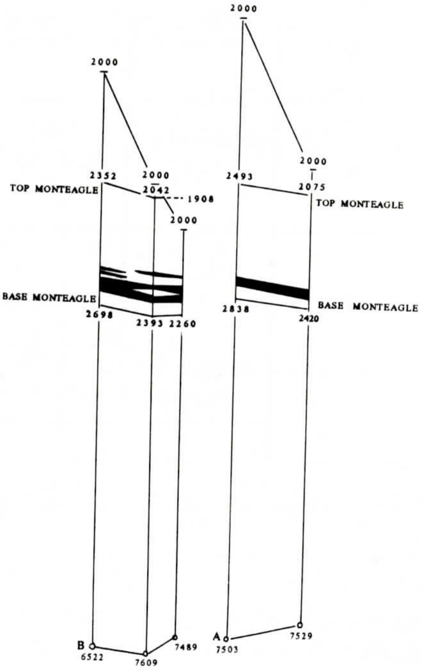

Figure 8, Panels A and B, Porous zone Distribution

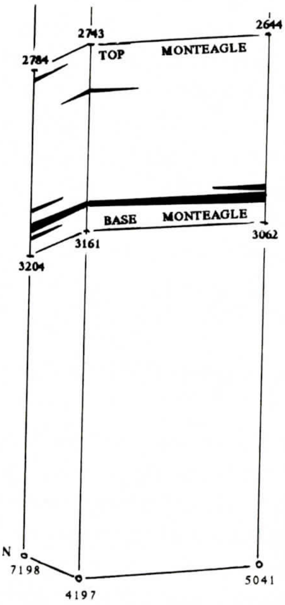

Figure 9. Panel F, porous zone distribution.

Cross-Section or Panel Diagrams

Panel diagrams of the Days Chapel Field diagrams depict elevations of the upper and lower contacts of the Monteagle Limestone as

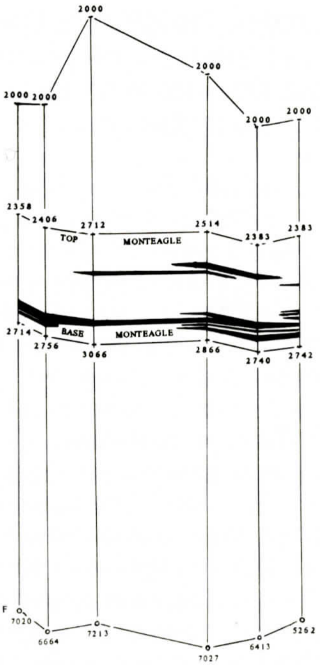

Figure 10. Panel N, porous zone distribution.

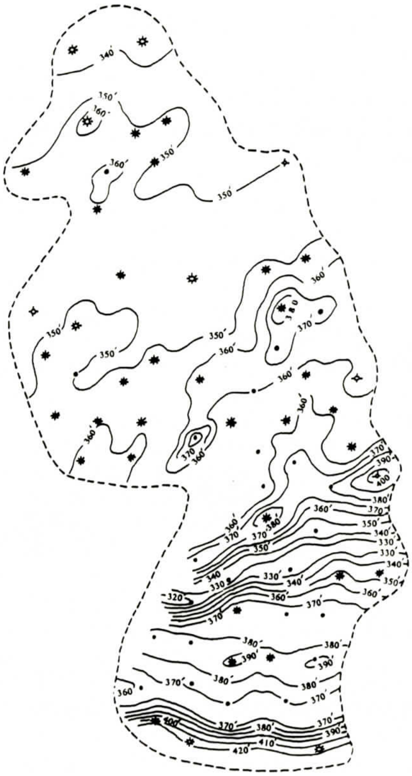

Figure 11. Isopach map of subsurface Mississippian Monteagle Limestone.

well as the stratigraphic position of porous zones that may contain oil and gas.

Figures 8-10 present panels A and B, F and N (Figure 6) and show the position of a major porous zone near the base of the Monteagle. In addition, they show the position of less-well-developed zones of porosity throughout the rest of the Monteagle.

Isopach Map

Examination of the isopach map of the Monteagle (Fig. 11) shows northeast-southwest-trending features that are interpreted to be similar to subsurface platform carbonate tidal bars situated in the foreland (Fentress, Morgan and Scott counties) of the Pine Mountain thrust block.

Aided by work of Lash (1988) and Reesman and Stearns (1989), Bergenback (1994) reported that Upper Ordovician through Carboniferous strata beneath the Cumberland Plateau in Tennessee show indications of having responded to tectonic forces in the northeast differently than in the southwest part of the plateau. The response of the Virginia Promontory and Tennessee Reentrant (part of an irregular continental margin) to these stresses produced Paleozoic forebulges such as the isostatically repressed Cumberland Plateau Dome.

In the southwestern portion of the Cumberland Plateau, within the Tennessee Reentrant, Silurian through Carboniferous strata accumulated under conditions of generally steady subsidence over the Cumberland Plateau Dome. Handford (1978) studied 18 outcrop sections of the Monteagle Limestone within the Tennessee Reentrant and recognized tidal bars covered by emergent tidal flats.

In the northeastern Cumberland Plateau area, the Cumberland Plateau Dome behaved like a forebulge that was uplifted and eroded. The stratigraphic section atop this forebulge is marked by unconformities caused by vertical oscillations related to thrusting during Acadian and Alleghenian tectonic events. An isopach of the Monteagle in the subsurface of the Oneida

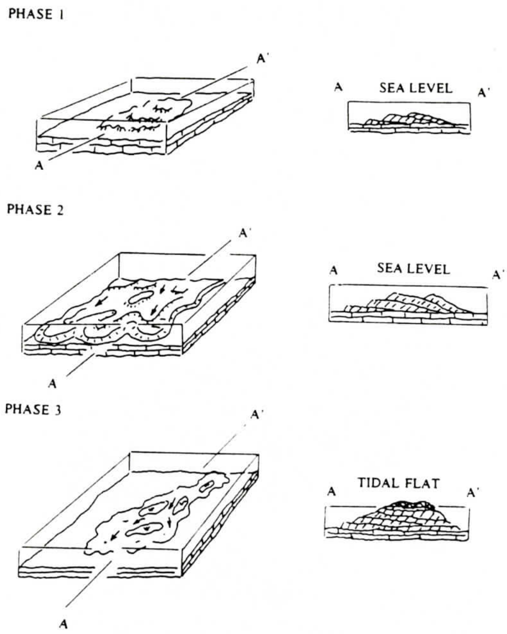

Figure 12. Three phase development of tidal bars in outcrops of Monteagle Limestone, after Handford (1978).

South quadrangle shows a number of mound-like build-ups, reminiscent of the tidal bars of Handford (1978). These bars trend northeast-southwest, have up to 15-18 meters of relief, and are as long as1.6 kilometers. In addition, Monteagle porous zones (shown on panel diagrams) are largely confined to the build-ups and occur in a laterally discontinuous manner at eight to ten distinct stratigraphic levels.

The structure contour map of Figure 7 was superimposed on the isopach map of Figure 11, with the view of determining if the general northeast-southwest-trending anticlinal and synclinal folds of the subsurface Monteagle are associated with thick and thin Monteagle tidal bar (northeast-southwest) trends. In other words, anticlines would be associated with thicker parts of the Monteagle and synclines with thinner parts. These analyses between structure and thickness showed little relationship.

SOME THOUGHTS ON DEVELOPMENT OF POROUS ZONES IN THE MONTEAGLE LIMESTONE

Suller, Budd and Harris (1994) discussed ideas from a Hedberg conference which considered porosity development in carbonate rocks, particularly that developed along unconformities. They list ten types of information they consider critical in determinig subaerial unconformities and associated carbonate rock porosity: (1) cores, (2) outcrops, (3) seismic data, (4) eustatic sealevel curves, (5) wireline logs, (6) biostratigraphic data, (7) stable isotope trends, (8) cycle-stacking patterns, (9) tectonic and (10) basin evolution models. Further, these authors recommend utilization of as many of these ten criteria as possible in recognizing subaerial exposure porosity, but even then, recognition is limited. At this point, it is necessary to point out that the subsurface porous zone distribution in this Days Chapel Field was mapped by using only bulk density and porosity graphs; a procedure that pales before the above-listed ten criteria. Nonetheless, Figures 8-10 portray the distribution of a major porous zone situated near the base of the Monteagle which is, in turn, overlain by less-well-developed porous zones throughout the rest of the Monteagle. Further, it is generally accepted that Mississippian stratigraphic units in the Cumberland Plateau area form a carbonate platform sequence perhaps similar to the modern Bahama Islands. Also, it must be remembered that this Days Chapel Field is contained with the Pine Mountain Thrust Block which has moved thirty kilometers to the northwest from its original site of deposition which was well to the east of the Cumberland Plateau Dome forebulge (Bergenback, 1994), but still on a carbonate platform west of a foredeep. Perhaps it was in a tectonic setting of flexure between a foredeep and a forebulge that subaerial exposure of carbonate clastics formed the localized unconformity now situated near the base of the Monteagle Limestone (Days Chapel Field).

The origin of laterally discontinuous porous zones at several stratigraphic levels above the basal porous zone in the Monteagle might be explained in the following manner. Smart and Whitaker (1991) point out that hydrologic systems associated with subaerial exposure of carbonate clastics may be divided into: (1) marine, (2) oceanic and (3) continental deposits. They consider oceanic deposits to be of large areal extent and relatively long-lasting. Modern examples are Caribbean and Bahamian Islands. These oceanic deposits are characterized by unstable mineralogies, small freshwater systems and repeated periods of rather short subaerial exposure on the order of thousands to tens of thousands of years.

Support for the work of Smart and Whittaker (1991) is given by Pace, Mylroie and Care (1992) who have documented vertical dissolution features in Pleistocene clastic carbonates on San Salvador Island, Bahamas. Here, they have identified two general types; (1) banana holes and (2) pit caves along with a few transitional types. Banana holes are wider than deep and occur at elevations below 6 meters. They were formed in a freshwater lens during a past highstand of sea level and are likely the result of roof collapse into underlying phreatic chambers.

Pit caves are deeper than wide and are generally situated at elevations above 6 meters. In addition, they are found near crests of calcarenitic eolianite ridges at elevations much higher than any ancient highstand of sea level. Pit caves are largely formed in the vadose zone and are produced by the downward movement of meteoric water through a complex system of surface and subsurface channels. Thus, in modern emergent platform carbonate islands, caves (porous zones) are developed and it seems reasonable to hypothesize that porous zones in ancient Mississippian Monteagle tidal bars are analogous in origin to banana holes and pit caves as developed in Pleistocene rocks on San Salvador Island, Bahamas. Unfortunately, in this case (Days Chapel Field), it is difficult to assign subaerial exposure unequivocally to either isostatic or eustatic activity.

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