ACROSS THE BREVARD ZONE:
THE CHATAHOOCHEE TUNNEL,
COBB COUNTY, GEORGIA

EDITED BY:
RANDY L. KATH, P.G. AND THOMAS J. CRAWFORD, P.G.

36TH ANNUAL FIELD TRIP
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INTRODUCTION
The proposed alignment of the Chattahoochee Tunnel, Cobb County Water System, crosses approximately 9.5 miles (15.3 km) of igneous and metamorphic rocks of the Piedmont/Blue Ridge geologic province. Unpublished and published maps by Higgins and others (1997) and Higgins (1968), respectively, used for the alternative alignment study by Jordan, Jones and Goulding, Inc. (JJG) showed numerous faults crossing the proposed alignments. These faults were shown as either dip-slip (thrust faults) and/or strike-slip (right-lateral and/or left-lateral) faults by Higgins and others (1997). However, the geotechnical nature (rock characteristics and potential for ground water inflows) along these faults has not been addressed. The purpose of this report is to address the geotechnical and hydrogeologic characteristics of these faults based on the published literature and detailed geologic mapping along the final alignment by Kath and Crawford (1999).

It should be noted that the authors have excerpted only the most pertinent data from the literature. A comprehensive reference list is provided at the end of this report for other publications related to the Brevard Zone in the southeastern United States.

Although the unpublished maps of Higgins and others (1997) were used for the alternative alignment study, the final design work is based on detailed, alignment-specific geologic mapping (see Kath and Crawford, 1999). The detailed geologic mapping included: lithologic identification, textural characterization, and measurement of structural features (i.e., foliation(s), lineation(s), joints, faults, compositional layering, fold axes, axial planes, crenulation axes, etc.) This alignment-specific detailed geologic mapping greatly enhanced the understanding of the geologic framework being transected by the Chattahoochee Interceptor Tunnel. This geologic framework is incorporated into the following discussions related, either directly or indirectly, to concerns about ground water along faults that may be encountered during tunnel exploration and construction.

The most current alignment of the Chattahoochee Tunnel will cross nearly the entire width of the Brevard Zone in Cobb County, as well as lithologic units northwest of the Brevard. This report presents:

♦ A discussion of the various published interpretations of the nature of the Brevard Zone (referenced figures can be found in the original publications),
♦ A reference to a broader “tectonic synthesis” of the U.S. Appalachians, and
♦ A summary of observations, interpretations, and conclusions directly related to the area of the Chattahoochee Tunnel.

BREVARD ZONE-
The most extensive and detailed study of the Brevard Zone in this area was done by Thomas J. Crawford and Jack H. Medlin in the late 1960’s and early
1970’s. Parts of the published works resulting from this study are presented here as a general overview of the Brevard Zone. For a more complete overview, the reader is referred to the original report by Medlin and Crawford (1973).

“Stratigraphy and Structure Along the Brevard Fault Zone in Western Georgia and Eastern Alabama,” by Medlin and Crawford

“Stratigraphy and Structure Along the Brevard Fault Zone in Western Georgia and Eastern Alabama,” by Medlin and Crawford, was published in the American Journal of Science, Cooper Volume, 273-A, 1973, p. 89-104. The following are excerpts from that volume.

Introduction

Much confusion is associated with the term Brevard. Contributing to the confusion concerning the Brevard is the use of this name for two distinctly different and possibly unrelated features, or different names applied to the same features. Keith (1905) originally applied the name “Brevard Schist” to a sequence of rocks exposed near the town of Brevard in Transylvania County, N.C. The Brevard Fault (cataclastic zone) cuts through or is in Keith’s “Brevard Lithologies” near there. However, subsequent work has shown that the two features are not always coincident as the Brevard cataclastic zone is traced southwestward. Instead, the Brevard Fault (Zone) deviates from the stratigraphic sequence and indeed crosses and separates parts of it in Georgia (comment by A.S. Furcron in King, 1955, p. 358; Medlin and others, 1972). Early usage of terminology and lack of detailed fieldwork have perpetuated the idea that the Brevard Fault Zone and stratigraphic sequence are inseparable— an assumption that is incorrect but that still persists.

A search of the literature points out very emphatically that the name “Brevard” has been appended to so many different, and often poorly defined, features that it has contributed to confusion and hindered correlation of work between various areas of the piedmont. In the western Georgia-eastern Alabama areas we have used the term Brevard only to refer to a fault zone, the Brevard Fault Zone, herein defined as a linear zone of penetrative movement.

Confusion has resulted also from the idea that the Brevard Fault Zone separates different “geologic belts”. This concept has been especially prevalent in North Carolina and South Carolina, where the crystalline rocks have been divided into geologic belts such as the Charlotte Belt, Inner Piedmont, Brevard Belt, and the Blue Ridge Belt (King, 1955; Overstreet and Bell, 1965; Griffin, 1971; Hatcher, 1972). Indeed, Hatcher (1972) and Griffin (1971) have now projected these belts into areas of Georgia and Alabama where little work has been done or where research has shown the concept to be untenable. This belt concept, while useful in reconnaissance-scale mapping, is not applicable when applied to detailed work in the western Georgia and eastern Alabama Piedmont (Crawford and Medlin, 1973; Long, 1971). Our studies have shown that these belts do not exist in these areas (Crawford, 1971). Hatcher (1969) has mapped the Brevard Fault Zone as separating the Inner Piedmont Belt from the Blue Ridge Belt in South Carolina, a proposition that does not hold as the belt is traced southwestward into western Georgia and eastern Alabama. Neither the Blue Ridge geologic province nor the Blue Ridge physiographic province extends into these areas, or, if they do, it has not been documented. The Brevard Fault Zone extends across the Piedmont of western Georgia and eastern Alabama, crossing stratigraphic and structural entities.

Purpose and Scope of Present Work

The present paper concerns the segment of the Brevard that extends from Atlanta, Ga., southwestward to Roanoke, Ala., a distance of about 128 km (80 miles). Our work has been concentrated on determining (1) a mappable litho-stratigraphic sequence for this part of the Brevard, (2) the structural styles exhibited by rock units within the Brevard, and (3) whether a correlation exists between the stratigraphy found within the Brevard Fault Zone and that found northwest of the Brevard Fault Zone and along the strike of the Brevard.

Previous Work

Since Keith’s initial work on the Brevard schist (1905) and the accompanying topographic lineament, a multitude of hypotheses to explain this fault zone have been published. The various hypotheses for the Brevard lineament include:

1. A tightly infolded syncline of Cambrian rocks, resting unconformably on the Precambrian (Keith, 1905, p.5).
3. A thrust fault comprised of several faults in a zone of distributed movement (Crickmay, 1952, p. 48).
5. A “dejective zone” (King, 1955).
6. A right-lateral strike-slip fault (Reed and Bryant, 1964).
9. An isoclinal synform with one or more episodes of faulting superimposed. Right-lateral strike separation of the fault can be explained by right-lateral strike slip or by normal-slip (Dunn, Butler, and Weigand, 1968).
10. A cataclastic zone separating low-rank Brevard-Poor Mountain-Henderson lithologies from the Blue Ridge (Hatcher, 1969).
11. “... The Brevard... may be part of a major fault system which moved deep seated infrastructure rocks of the Inner Piedmont northwestward over shallower seated superstructure.” (Bentley and Neatherly, 1970, p.1).
12. A combination thrust and left-lateral strike-slip (Reed, Bryant, and Meyers, 1970).

The hypotheses concerning the Brevard are more varied than the belt or fault(s), as is evidenced below by the variety of conclusions reached by researchers studying different areas of the problem since 1964.

In 1964, after detailed mapping along parts of the Brevard belt in North Carolina, Reed and Bryant concluded that “... the Brevard is a fault zone. Further, the data... suggest that the Brevard is a zone of strike-slip faulting of great magnitude. Right-lateral displacement of at least 135 miles is believed to have occurred in the late Paleozoic or Early Tertiary time or both” (Reed and Bryant, 1964). This work was the impetus for much of the work that followed. Overstreet and Bell (1965) concluded that the Brevard belt is “… a great strike-slip fault on which the horizontal displacement appears to have been too great to be measured in South Carolina alone”.

Higgins (1966, 1968), after rather extensive work on the Brevard lineament in the vicinity of Atlanta Ga., concluded that “The Brevard consists of retrograded rocks and cataclastic rocks believed to be the result of movement (right-lateral and reverse) on a major fault zone”. He included in the “Brevard Lineament” a number of rock units which he named the “Sandy Springs Sequence.”

Higgins’ work was followed by Burchfiel and Livingston (1967) who published an interpretative paper on the Brevard Zone, based on published data, and compared the Brevard Zone to alpine root zones. In a general way, this interpretation has been continued by Hatcher (1971b) in his work in Rabun and Habersham Counties, Ga. Butler (1971) suggests that the Brevard Zone is a root zone but with significant differences from the alpine-type root zones.

Work by Butler and Dunn (1968) in the Sauratown Mountains area of North Carolina states that “Rocks of ‘Brevard zone affinities’ ... define an erect synform (James River Synclinorium in Stokes and Surry Counties)”. In summary, they refute the root zone suggestion of Burchfiel and Livingston (as pertains to Surry and Stokes Counties).

Work by Hatcher (1969) on the Brevard of northwest South Carolina led him to conclude that the “low-rank belt” is a large synclinal infold, sharply separated from the Blue Ridge by the Brevard cataclastic zone, and overridden from the southeast by higher rank nappes of the inner Piedmont. In later papers Hatcher (1970, 1971a, 1971b) considers the Brevard Zone to be localized in the northwest limb of the Low Rank Belt synclinorium and interprets this as a later thrust related to the Blue Ridge thrust system. Hatcher states further that the persistence of the same stratigraphic units along the Brevard Zone indicates stratigraphic control of faulting within the structure (Hatcher, 1972).

In a recent paper Reed, Bryant, and Myers (1970) explain the Brevard as a left-lateral strike-slip fault with simultaneous northwest thrusting.

Watkins (1971a, 1971b) interpreted the Brevard Zone on the basis of geophysical work and concluded that it is a fossil Benioff Zone.

From studies of the mesoscopic fabric of the Brevard Zone in Surry and Stokes Counties, N.C., Stirewalt and Dunn (1971) suggested that the zone is an isoclinal synform.
Bentley and Neathery (1970, p.2), working in Alabama, suggest that the (Brevard) “…blanket of metasedimentary rocks appears to have been the floor of a large nappe of infrastructure rock moving from the southeast.”

Hurst (1970) in discussing the Georgia Piedmont, states that, “Until more field data are available and until it can be shown conclusively that the rocks on the two sides of the zone (Brevard) are dissimilar, the possibility of the Brevard Zone being a major fold complicated by trough faulting rather than a strike-slip fault should not be ruled out.”

**Metamorphism and Texture**

All the rock sequences of the Brevard Fault Zone have been affected to some extent by cataclasis. Breccias, ranging from 5 mm up to 3 cm, are present in some areas, but for the most part the cataclasis has resulted in textural changes that include: shredding of the micas; granulation of quartz, feldspar, and garnet; button-shaped concentrations of graphite in the graphic schist; changes in the shape of quartz (augen), feldspar (augen), micas (bent), kyanite (bent), garnets (flattened, sheared into thin plates), and staurolite (flattened). The combination of these textural changes combined with good development of S₃ (cataclastic foliation) in some places, produced button schist, phyllonite, mylonite, or ultramylonite.

These types of cataclastic rocks are quite well documented by Higgins (1966, 1968, 1971).

Vein quartz in the cataclastic zones has cataclastic textures- granulated, ribbon, or ribbon-and-eye. In many places of intense weathering these textures in vein quartz are the only indication of cataclasis.

There is little mineralogical difference between rocks within the Brevard Fault Zone and rocks outside the zone. Along the strike length we have studied, rock units within the Brevard Fault Zone have been regionally metamorphosed to the kyanite grade and, locally, sillimanite, but later retrograded.

Throughout the sequences, the rocks contain abundant garnet, staurolite, kyanite and, locally, sillimanite. These minerals, characteristic of the Barrovian facies series, indicate that this stratigraphic pile, some 128 km (80 miles) in strike length, has been metamorphosed to the kyanite grade and, locally, to the sillimanite grade. The absence of these index minerals appears to be more a function of chemical composition of the parent rock than of attendant P-T conditions, or of any rapid change in the ambient P-T conditions under which the rocks were metamorphosed. Supporting this conclusion is the widespread presence of these metamorphic index minerals in rock layers enclosing rocks without the index minerals and the alternating occurrence and absence of these index minerals over a distance of several meters, along thin folia of one rock.

The rocks in this area have been, however, subjected to retrogressive metamorphism, as evidenced by the widespread occurrence of chlorite replacing biotite and mica replacing kyanite and staurolite. Chlorite is particularly abundant in rocks associated with the major cataclastic zones and alteration zones (Hurst and Crawford, 1969). Ultramafic pods, which occur in the metasedimentary pile, are also extensively altered to chlorite, talc, serpentine, and anthophyllite.

In many of the cataclastic rocks, two generations of garnet are present: one is sheared, and the other is unsheared, indicating garnet growth after cataclasis. Supporting evidence for growth after cataclasis is found in some ultramylonites which contain euhedral garnet as large as 1 cm across. Preliminary microprobe analysis on both sheared and unsheared garnets indicate that there is little if any chemical difference in the two generations of garnets. Growth of the retrograde minerals found within the rocks is thought to have accompanied the cataclastic or faulting episode(s).

The rock sequences (D through J) described in this paper correlate in part with the Sandy Springs Sequence of Higgins (1966, 1968). The same rock units, in all probability, correlate in part with those mapped by Hurst (1956) in the Kennesaw Mountain-Sweat Mountain area of Cobb County, Ga. In Douglas County, Ga., the lithologic sequences (D through J) occupy a broad area, but southwestward along strike, the outcrop width narrows because of the plunging out of folds, and faulting along both the southeastern and northwestern margins. Higgins (1968) shows the Sandy Springs Sequence in Douglas County to be cut off or interrupted along its southeastern margin by a mylonitic gneiss along which he places the Long Island Fault. This mylonitic gneiss (the porphyroclastic and porphyroblastic gneiss described earlier in this paper) is one of the most persistent lithologic units within the stratigraphic sequence. It is biotite-muscovite-plagioclase-quartz-microcline gneiss fine- to medium-grained, with locally developed feldspar porphyroclasts. The outcrop width of this unit rarely exceeds 180 m (600 ft) but along strike it has been traced for more than 128 km (80 miles). There is little
discernable compositional variation along strike over this distance. This remarkable persistence and the fact that the unit maintains the same relative position in the sequence suggest that this rock unit was originally of sedimentary origin and did not originate through faulting (Higgins, 1966, page. 36). Texturally, mineralogically, and stratigraphically this rock appears to correlate with the Austell Gneiss (C) which wraps around the nose of the Austell-Frolona anticlinorium (Crawford and Medlin, 1973). The absence of the Austell Gneiss along a part of the southeastern flank of the Austell-Frolona anticlinorium is attributed to the high-angle reverse fault in that area.

The continuation of the Long Island Fault of Higgins (1968) is indicated by the fact that part of the stratigraphic sequence is apparently cut out along the southeastern flank of the synclinorium and by the cataclastic nature of the rocks in this area along the entire length of the Brevard.

Structure

Along a strike distance of some 128 km (80 miles), lithologic mapping combined with structural and textural mapping has shown that the northeast-trending Brevard lineament is comprised of zones that have been intensely sheared and granulated, bounded by rocks that have undergone little cataclastic deformation. In places, the contacts are sharp and deformation has been concentrated within particular lithologic units or along restricted zones within a lithologic unit.

Within the Brevard Fault Zone, folds are dominantly overturned to the northwest, asymmetrical, and doubly plunging folds (figs. 3,4,5,6,7, and 8). The major zone of cataclasis cuts across these folds without demonstrable offset of lithologic units as shown by mapping of units through zones of cataclasis. Major folding occurred prior to mylonization, for the cataclastic zone is not folded; however, minor folds within the mylonites indicate some post-cataclasis compression (post-faulting). The coherence of the rock and the presence of unsheared garnets suggests that faulting and cataclasis took place at elevated temperatures.

Outcrop patterns of lithologic sequences within the Brevard Fault Zone define doubly plunging folds. These folds have $S_1$ (bedding) and $S_2$ (schistosity and gneissosity) coincident, with a well-developed $S_3$ cleavage that crosses $S_1$ and $S_2$ and at a slight angle. The trend of the $S_3$ cleavage is to the northeast with a dip to the southeast. Equal-area plots of the linear features (crinkle axes, mineral alignment, and striations) within the Brevard Fault zone support the lithologic definition of the folds. The dip of the rock sequences described above, based on more than 300 readings, ranges from 50 to 70 degrees to the southeast.

Within the Brevard Fault Zone, the effects of the faulting or movement on lithologies are first discerned by the appearance of the $S_3$ surface. This third surface is not well developed along the fringes of the Brevard Fault Zone but becomes more easily recognized inward from the margins. Within zones of intense shearing it becomes the dominant S-surface, and the need for lithologic mapping, in addition to textural mapping, is very important. Labeling units as button schist, mylonite, mylonitic schist, or mylonitic gneiss, without indicating primary lithology, is of little value when attempting to correlate these cataclastic units with rocks outside the movement zone. The presence and degree of development of a third S-surface in rocks of the western Georgia and eastern Alabama Piedmont are directly related to their proximity to cataclastic zones such as the Brevard. Northwest of the Brevard Fault Zone, the $S_1$ and $S_2$ surfaces are coincident and wrap around the fold noses. This is well illustrated by the Austell-Frolona anticlinorium (Crawford and Medlin, 1973).

In the northeast (Douglas County, Georgia) and southwest (Randolph County, Alabama) parts of the study area, cataclastic deformation of the Brevard Fault Zone is distributed over a broader area than in the intervening 80 km (50 miles). This splaying or broadening of the cataclastic zones coincides with the opening of major folds within the stratigraphic sequence.

Along the northwest side of the previously described stratigraphic sequence, a part of the lithologic section is missing. Geologic mapping (figs. 3-8) indicates a reverse fault truncating these units for the entire length of the study area (figs. 3,4,5,6,7, and 8). This fault, called Chattahoochee Fault by Hurst (1973), parallels the southeastern side of the Austell-Frolona anticlinorium for approximately 96 km (60 miles). For part of this distance, this fault is coincident with what has been mapped as the Brevard Fault Zone. In Douglas County, the fault diverges from the northeast trend of the Brevard Fault Zone, passes around the nose of the Austell-Frolona anticlinorium in Cobb County, and assumes a more northerly trend (fig. 8).
In Randolph County, Ala., a zone of intense cataclasis, tentatively correlated with the Omaha Fault of Bentley and Neathery (1970), along the northwest side of the Brevard Fault Zone, turns northerly and crosses the southwestern part of the Austell-Frolona anticlinorium. This fault zone has been traced to the northeast across Randolph County, Ala. and Heard County Ga., and to the north along the west flank of an anticlinal structure in Carroll County, Ga. (Crawford and Medlin, 1973).

Conclusions
Detailed mapping indicates that the rocks underlying the “Brevard belt” in western Georgia and eastern Alabama can be divided into twelve lithologic sequences that define a synclinorium more than 128 km (80 miles) in length. The lithologic units correlate in part with stratigraphy presented by Higgins for the Atlanta area (1966, 1968). These rock units are mostly sedimentary in origin and have been metamorphosed to the staurolite-kyanite and, locally, to the sillimanite grade of regional metamorphism. The metamorphism accompanied folding in the area; faulting occurred during the waning stages of folding and metamorphism. Compressional forces produced asymmetrical, doubly punging folds within the “Brevard belt” rocks. A reverse fault occurs along the northwest limb of the synclinorium and another fault, in all probability a continuation of the Long Island Fault (Higgins, 1966), is present along the southeastern side of the rock sequences, subparallel to the southeast limb of the synclinorium. The Brevard lineament, or the zone of most intense cataclasis along the Brevard topographic lineament.

The faulting in the study area is controlled by major fold structures such as the Austell-Frolona anticlinorium and the synclinorium defined by the rocks of the “Brevard belt”. It is not stratigraphically controlled. In all likelihood, those rocks found within this synclinorium are correlative with those that flank the Carroll-Paulding synclinorium northwest of the Brevard Fault Zone (Crawford and Medlin, 1973); in part with rocks described by Hatcher (1972) in the Chauga belt of northeast Georgia and northwestern South Carolina; and in part with those rocks described by Hurst (1956) in Cobb County, Ga.

“Cataclastic Rocks,” by Higgins
In his 1971 U.S. Geological Survey Professional Paper (687) entitled “Cataclastic Rocks,” Michael Higgins describes the cataclastic nature of some of the rocks within and near the “Brevard Zone.” The following are excerpts from that publication (pages 49-51).

The Brevard Zone, Southeastern United States
The Brevard zone is a belt about 1 to 5 miles wide of cataclastic and low-grade metamorphic rocks that extends northeast in a nearly straight line from eastern Alabama nearly to Virginia (fig. 27). Throughout this course the zone is bordered on either side by plutonic and higher-grade metamorphic rocks. Approximately coincident with the belt from near Wilkesboro, N.C., to about Tallapoosa River in Alabama is a marked topographic lineament (see U.S. Army Map Service plastic relief 1:250,000-scale series maps: Atlanta-NI 16-9; Greenville-NI 17-4; Knoxville-N17-1; Charlotte-NI 17-2; and Winston-Salem-NJ 17-11). A distinctive magnetic lineament is also coincident with the Brevard zone for at least part of its course (Philbin and others, 1964). The southern end of the Brevard zone in Alabama was assumed to bend to the south near Tallapoosa River to reach the edge of the Coastal Plain just northeast of Montgomery (U.S. Geol. Survey and Am. Assoc. Petroleum Geologists, 1961; King, 1964; Reed and Bryant, 1964; Bayley and Muehlberger, 1968). However, recent work in that area shows that the zone probably splays southwest of Tallapoosa River; subsidiary zones bend gradually south, but the main zone continues on its southwest course to pass beneath the edge of the Coastal Plain near Central, Ala. (Bentley, 1969; Bentley and Deininger, 1969; Bentley, oral commun., 1969; fig. 27). A somewhat similar situation exists for the northern end of the Brevard zone, in North Carolina. On most maps (U.S. Geol. Survey and Am. Assoc. Petroleum Geologists, 1961 King, 1964; Reed and Bryant, 1964), the Brevard Zone is shown continuing along a straight northeast course past Mount Airy and into Virginia, but recent work (Dunn and others, 1966; Espenshade, 1967; Butler and Dunn, 1968; Centini, 1968) indicates that the zone begins to splay near Wilkesboro. One branch bends east to become the Stony Ridge fault zone; another branch bends eastward toward Pilot Mountain; and still another branch bends slightly eastward and follows a conspicuous topographic lineament through Ararat, between Mount Airy and Pilot Mountain (fig. 27).
From near Wilkesboro, to near Fletcher, N.C. (fig. 27) the Brevard zone is a belt of phyllonite, blastomylonite, and mylonite gneiss, about a mile wide, near the northwest edge of a zone of shearing and retrogressive metamorphism about 5 miles wide (see Reed and Bryant, 1964). Rocks quite similar to those in the segment from Wilkesboro to Fletcher occupy the two westernmost branches or splays northeast of Wilkesboro; the easternmost branch, the Stony Ridge fault zone, is characterized chiefly by microbreccia. The description of the Wilkesboro to Fletcher segment of the zone also fits the segment from Fletcher southeast to near Flowery Branch, Ga., except that this segment also contains discontinuous lenses of dolomitic marble, which Reed and Bryant (1964) consider “exotic tectonic lenses.” Southwest of Flowery Branch, at least to Tallapoosa River in Alabama, phyllonites, blastomylonites, and mylonite gneisses identical to those in the zone to the northeast are joined by thin, discontinuous, and commonly en echelon bands of mylonite, protomylonite, ultramylonite, microbreccia, and cataclasite. Polycataclastic rocks, chiefly brecciated mylonite, are also present in this segment. In Georgia, the main band of cataclastic rocks is locally more than 2 miles wide, but the zone of shearing and retrogressive metamorphism is generally thinner than in North Carolina. Southwest of Tallapoosa River the Brevard zone and its branches have not yet been studied in detail, but it appears that the rocks there are similar to those of the Flowery Branch to Tallapoosa River segment.

The character and origin of the Brevard zone is currently in dispute. Some geologists have presented evidence that it is a great strike-slip fault with some vertical displacement (Reed and others, 1961); King, 1964; Reed and Bryant, 1964; Higgins, 1966); others believe it is an “alpine type root zone” or zone of “Verschluckung” (Burchfiel and Livingston, 1967, 1968; Livingston and Burchfiel, 1968); still others recognize sedimentary characteristics in the zone (Hurst and Crawford, 1964; Dunn, Butler, and Justus, 1968; Dunn, Butler, and Weigand, 1968). Nevertheless, the presence of cataclastic rocks in the zone is indisputable.

Reed and Bryant (1964, p. 1182-1183) gave a vivid “verbal cross section” of the southeast border of the Brevard Zone in North Carolina:

> The rocks of the Inner Piedmont more than 5 miles southeast of the Brevard zone are all of high metamorphic grade and display no conspicuous cataclastic features. The plagioclase is generally andesine; aluminous rocks contain sillimanite, and calcareous rocks contain diopside. Foliation has diverse strikes and low to moderate dips, generally to the south or southeast. Lineation is marked by alignment of fibrous sillimanite and prismatic hornblende, by elongate clots of biotite and by crenulations in foliation planes and generally plunges gently or moderately eastward. The mineral alignment is apparently due to growth parallel to crenulation axes.

About 4 miles from the Brevard zone the metamorphic grade is lower. Sillimanite disappears, although staurolite and kyanite are found locally; polymetamorphic textures become increasingly apparent. Foliation assumes a consistently northeast strike, parallel to the Brevard zone, and subhorizontal cataclastic lineation parallel to the strike becomes prominent. This lineation is marked by streaks of fine recrystallized mica on foliation planes, crushed and drawn out feldspar porphyroclasts, and aligned aggregates of recrystallized quartz. Long axes of boudins of amphibolite and of competent lime-silicate rocks in the gneisses are generally parallel to it. Axes of isoclinal folds also generally trend northeast, but many display steeper and more erratic plunges. Within 2-3 miles of the Brevard, rocks of the Inner Piedmont belt are conspicuously cataclastic and polymetamorphic. The schists contain porphyroclasts of muscovite, plagioclase, and locally of staurolite and kyanite set in a matrix of fine-grained, recrystallized quartz, biotite, muscovite, epidote, and plagioclase. Both the plagioclase porphyroclasts and the fine-grained recrystallized plagioclase are either oligoclase or sodic andesine, indicating recrystallization under medium-grade conditions.

Adjacent to the Brevard zone the medium-grade polymetamorphic rocks are retrogressively metamorphosed to low grade: plagioclase is partly or completely altered to albite, and biotite is replaced by chlorite. The textural contrasts, as the
Brevard zone is approached, are particularly conspicuous in the Henderson Gneiss. Fine-grained biotite-quartz monzonite gneiss containing large augen of microcline is reduced to blastomylonitic gneiss (mylonite gneiss of my classification; table 1) and finally to blastomylonite in and near the Brevard zone.

For the most part, the rocks in the Brevard zone are typical cataclastic rocks like those defined, described, and illustrated elsewhere in this paper. However, two types of rock in and near the zone are particularly interesting, chiefly because identical rocks occur in association with the Brevard throughout its extent: (1) Porphyroclastic phyllonites, called “phyllonitic schists” by Reed and Bryant (1964, p. 1181), and “muscovite-eyed phyllonites” by Higgins (1966, p. 27-28), occur intermittently in the Brevard zone from Alabama to northern North Carolina. These rocks typically have a lustrous gray, silvery-gray, gray-green, or blue-green phyllitic groundmass and contain bent porphyroclasts of muscovite or sericite, which have a “fish-scale” appearance on foliation planes and a ragged, “flagellate” appearance in cross section. These bent porphyroclasts of mica give the foliation planes a “curly” or “wavy” appearance. Reed and Bryant (1964, p. 1189) cited evidence that some of these rocks are diaphthoritic in the Grandfather Mountain Window area, but near Atlanta, GA., they may be simply phyllonitic (Higgins, 1956, p. 27); (2) Rocks called “button schists” by Higgins (1966, p. 27), and simply “polymetamorphic schists” by Reed and Bryant (1964) are intimately associated with the Brevard zone throughout its extent and have a remarkably identical appearance all along the zone. These rocks are not strictly cataclastic, because they have crystalloblastic textures, but it is obvious that they have been much sheared and recrystallized, and, in fact, they may be blastomylonites in which the crystalloblastic process has completely dominated cataclasis. They are characterized by two subparallel cleavages that cause distinctive buttons upon weathering (Crickmay, 1952, p. 26).

“Brevard Fault Zone in Western Georgia and Eastern Alabama,” by Crawford and Medlin

In 1974, Thomas J. Crawford and Jack H. Medlin led a fieldtrip for the Southeast Section, Geological Society of America. The purpose of this trip, as stated in the fieldtrip guidebook “Brevard Fault Zone in Western Georgia and Eastern Alabama” is pertinent to concerns in the area of the Chattahoochee Tunnel, and portions of that guidebook are presented here.

Purpose

The Purpose of this field trip, as indicated by the title, is to view the stratigraphy, structure, petrology, and geochemistry of the Brevard Fault Zone; specifically, to relate these features to cataclasis; and, in particular, to point out the relationship of a very obvious low topographic lineament (developed along a zone of intense cataclasis) to the overall geology of this area.

Higgins (1966, 1968) defined the Brevard (Fault) zone in parts of Douglas, Cobb, and Fulton Counties as being bounded on the northwest by a thin mylonite gneiss (coincident with the Long Island Fault), and on the southeast by sheared Palmetto Granite. Using this definition, the Sandy Springs Sequence is northwest of the Brevard Zone and the Brevard Zone coincides with a zone of intense cataclasis, which is coincident with a low topographic lineament.

Because of the limited amount of detailed work in this area until recently, it seems to have been assumed that the relationship between the Brevard (Fault) Zone (i.e., a (low) topographic lineament with a northeast-southwest trend) and “Brevard” lithologies is consistent in western Georgia; that the relationship would be the same as that published for Douglas-Cobb-Fulton Counties. Such is not the case.

Southwestward from Douglas County, the low topographic lineament (coincident with a zone of intense cataclasis) cuts across stratigraphic boundaries, across the Yellow Dirt gneiss (mylonite gneiss of Higgins), and across the Long Island Fault, so that in Carroll and Heard Counties, Georgia and Randolph County, Alabama, this lineament is within and on the northwest side of the Sandy Springs Sequence. Because this northeast-southwest trending lineament is so very conspicuous, it has received much attention from those attempting to interpret the regional structure and history of the southeastern Piedmont. However, there are numerous broad zones of intense cataclasis which splay off this lineament to the south and to the north, which have received no attention.

To further emphasize the importance of distinguishing between faults, fault zones, cataclastic
zones, and topographic lineaments, we will attempt to demonstrate with this field trip that major displacement within the Brevard Fault Zone has occurred along distinct faults within the zone, but that widespread and intense cataclasis occurred later and resulted in little displacement; and that these zones of intense cataclasis are not spatially coincident with major-displacement faults.

If this interpretation is valid, and evidence is sufficient to require consideration that it is, great care should be exercised in projecting (displacement) faults into unmapped areas, particularly on the basis of topographic lineaments, and using such projections as bases for making regional interpretations.

“*The Structure, Stratigraphy, Tectonostratigraphy and Evolution of the Southernmost Part of the Appalachian Orogen,*” by Higgins and others

In 1988, Michael W. Higgins and others, summarized “The Structure, Stratigraphy, Tectonostratigraphy and Evolution of the Southernmost Part of the Appalachian Orogen” in the U.S. Geological Survey professional paper 1475. The section on the Brevard Zone is presented here in its entirety; it is a good general summary of concepts developed to that time.

The Brevard Zone

The Brevard Zone is a narrow zone of sheared and low-grade-appearing rocks that extends from beneath the Coastal Plain in Alabama to southern Virginia. There have been more than twenty different interpretations and combinations of interpretations of the nature of this controversial zone (see reviews and discussions in Medlin and Crawford, 1973; Roper and Justus, 1973; Rankin, 1975; and references in all three). Many of these interpretations have invoked thrust faulting or strike-slip faulting, or some combination of the two, to explain the zone, but nearly as many have emphasized the stratigraphic nature of the zone. Still other interpretations involve some form of root zone, or a “Caledonide-like Abscherung-zone,” or a paleosubduction zone, or a complicated polytectonic zone in which isoclinal folds are formed and then sheared out during plate collision(s), or the suture zone between a Piedmont island arc and the North American continent, which was also the root zone for Blue Ridge thrust sheets, or the transported suture along which the proto-Atlantic Ocean finally closed.

Perhaps not surprisingly, our work indicates that the Brevard Zone is probably a combination of many of the previous interpretations in one sense or another, except for the root zone, Abscherungzone, transported suture, and paleosubduction zone interpretations. Our work shows that throughout Georgia and Alabama at least, identical stratigraphic sequences in the Bill Arp, Zebulon, Sandy Springs, Paulding, Ropes Creek, and Soapstone Ridge thrust sheets are found on both sides of the Brevard Zone (pls. 1,2) and that the only major sequences found on one side of the zone but not on the other are those in the Clairmont, Wahoo Creek, Atlanta, and Promised Land thrust sheets and the Little River thrust stack (excluding of course rocks in the Valley and Ridge province, including the Talladega Group, Rockmart Slate, and Athens Shale). This precludes the Brevard Zone being a fault of great magnitude, as predicted by Hurst (1970, 1973). It also nullifies the concept that the Blue Ridge and Piedmont are separate geologic belts, as pointed out earlier by Medlin and Crawford (1973) and Crawford and Medlin (1973), our work shows that no major thrust sheets in Georgia and Alabama are rooted in the Brevard Zone or anywhere near it.

The works of Hurst and Crawford (1964), Hatcher (1969), Hurst (1973), Medlin and Crawford (1973), Crawford and Medlin (1973, 1974), and Kline (1980), and our own work, clearly show that mappable stratigraphic sequences are present in the traditional Brevard Zone. We further suggest that different sequences within the zone are different thrust sheets in the Georgiabama thrust stack that have been sheared and generally incompletely retrograded. The rocks of the Brevard Zone were considered low-grade (and prograde) phyllites and schists by Keith (1905, 1970b), and Hatcher (1969, 1970). Our work confirms the conclusions of Jonas (1932) and Reed and Bryant (1964) that the low-grade appearance of the Brevard Zone rocks is due to retrogressive metamorphism. Relict staurolite, kyanite, and sillimanite have been found in the low-grade-appearing rocks virtually throughout the length of the Brevard Zone, from Alabama to northern North Carolina (Keith, 1905, p. 8; Reed and Bryant, 1964, p. 1181, 1183; Butler and Dunn, 1986, p. 43; Bentley and Neathery, 1970, p. 23-24; Hurst, 1970, p. 389; Roper and Dunn, 1971, 1973; Crawford and Medlin, 1973, p. 714, 719; 1974, p. 1-4; Medlin and Crawford, 1973, p. 99; Roper and Justus, 1973, p. 115).
In Georgia and Alabama rocks in the Brevard Zone are identifiable as belonging to several different thrust sheets in the Georgiabama thrust stack. Near Atlanta, Ga. (pls. 1, 2), the rocks in the Brevard are retrograded (locally graphitic) schists and phyllonites that are devoid of volcanogenic components and that belong to the Bill Arp thrust sheet. Just southwest of Atlanta, these rocks are structurally overlain by the Zebulon thrust sheet, and the shearing and retrogression typical of the zone have affected schists, amphibolites, and gneisses of the Zebulon Formation in the Zebulon thrust sheet. A short distance farther to the Southwest, the Zebulon sheet in the Brevard Zone is structurally overlain by the Sandy Springs thrust sheet and locally by slices of the Paulding thrust sheet, so that the shearing and retrogression have affected rocks of the Sandy Springs Group and locally the Paulding Volcanic-Plutonic Complex. The shearing and retrogressive effects appear to stay within the Sandy Springs Group and the part of the Jacksons Gap Group (Bentley and Neathery, 1970) that belongs to the Sandy Springs thrust sheet all the way to the Coastal Plain overlap in Alabama (pl. 1).

Northeast of Atlanta, the Brevard is mostly composed of rocks of the Bill Arp and Zebulon thrust sheets so closely folded together that we have not yet been able to divide them. Locally, rocks of the Sandy Springs sheet occur in the zone northeast of Atlanta.

The marbles in the Brevard Zone have most recently been considered to be Valley and Ridge carbonate-shelf-sequence rocks (Shady Dolomite or Knox Group rocks) brought to the level of the present surface by thrust faulting (Hatcher, 1971a; Hatcher and others, 1973; Hatcher, 1978a). Where we have seen these marbles they are always infolded with sequences of sheared pelitic rocks and sheared metagraywacke that lack amphibolites and appear to belong to the Bill Arp thrust sheet. We interpret the Brevard Zone metacarbonate rocks as representing the same depositional environments as the Murphy and Chewacla Marbles, though probably in a different Ocoee basin. Thus, the Brevard marbles may be roughly the same age as Valley and Ridge carbonate-shelf-sequence rocks, but they are probably not directly correlative with any of the carbonate-shelf-sequence units.

Our work has also demonstrated approximately 35 km of late right-lateral displacement along the Brevard Zone between Gainesville, Ga., and Suwanee, Ga. (pl. 1). Tightly folded stratigraphic sequences of Sandy Springs Group rocks in the Sandy Springs thrust sheet are present on both sides of the Brevard Zone in this stretch between Gainesville and Suwanee, as first suggested by Hurst (1973) and later shown by the detailed work of Kline (1980, 1981). Narrow, parallel, tight to isoclinal, northeast-trending anticlines and synclines, involving the distinctive Sandy Springs stratigraphic sequence, can be followed for many kilometers to the southwest; in the vicinity of Gainesville, they bend abruptly southeastward and terminate within (probably structurally above) a narrow outcrop belt of Bill Arp thrust sheet rocks that marks the center of the sheared and retrograded Brevard Zone there. Identical tight folds of the Sandy Springs Group on the southeast side of the Brevard trend southwest to the vicinity of Suwanee and then bend abruptly northwestward to terminate within the Brevard. The bending of the folds and the stratigraphic sequence on both sides of the Brevard Zone are interpreted to be the result of drag folding caused by right-lateral strike-slip faulting along an unseen fault or faults within the narrow zone. The measured displacement is approximately 35 km. Because the offset and drag affect the folds in the Sandy Springs thrust sheet, and because these folds probably formed after the Early Silurian (see above), strike-slip faulting is considered post-Early Silurian. The Carboniferous Ben Hill and Palmetto Granites near Atlanta, Ga., place further constraints on the age of the strike-slip faulting along the Brevard Zone in Georgia. Right-lateral faulting along the Brevard is suggested by the northeast-trending ‘tails” of the granites (pls. 1, 2), but no offset of stratigraphic sequences or other features has been found anywhere but in the stretch between Gainesville and Suwanee. The strike-slip faulting along the Brevard is probably post-Carboniferous and local.

There is also evidence of late normal faulting along part of the northwestern boarder of the Brevard Zone (W.A. White, 1950; Butler and Dunn, 1968; Roper and Dunn, 1971; Stonebraker and Harper, 1973; Roper and Justus, 1973) in which the southeastern side is down-thrown relative to the northwestern side. Like the strike-slip faulting, this normal faulting is probably post-Carboniferous.

Our interpretations of the pre-Carboniferous Brevard in Georgia and Alabama is akin to the interpretation of Roper and Justus (1973), but with some modifications. We suggest that the Brevard is a complex polytectonic zone of extreme flattening, insoclinal to elasticas (Fleuty, 1964) folding, and shearing that formed continuously in parts of the thrust sheets beneath and in front of the advancing Clairmont and higher sheets in the Georgiabama thrust stack, and that the Brevard was transported...
cratonward along with the stack. It probably started forming far from its present position as the Clairmont thrust sheet moved onto the underlying Zebulon thrust sheet causing isoclinal folding and shearing of the Zebulon sheet and underlying Bill Arp sheet immediately in front of and beneath the leading edge of the Clairmont and the thick stack of sheets above the Cairmont. As the stack of moving thrust sheets continued to advance, rocks in the zone were continuously refolded, flattened, mylonitized, and remylonitized. Isoclinal folds were almost continuously being formed and then sheared out in different parts of the zone (Roper and Justus, 1973), but vestiges of the original stratigraphic sequences survived in many places, especially in upfolded parts of the Bill Arp sheet and in the Sandy Springs, Paulding, Ropes Creek, and Soapstone Ridge thrust sheets, which only became involved and invold in the Brevard Zone after their leading edges had overridden the leading edge of the Atlanta and Promised Land sheets but while the greater parts of the sheets were still on top of and moving with the Promised Land and lower sheets (p. 2).

Thus, the Brevard Zone is a kind of suture zone only in the sense that it is the frontal “suture” of the far traveled, allochthogenetic Clairmont, Wahoo Creek, Atlanta, and Promised Land thrust sheets. It could also be considered a kind of very complicated tectonic melange formed in front of and beneath a thick stack of thrust sheets.

TECTONIC SYNTHESIS OF THE U.S. APPALACHIANS-


Chapter 14 of that volume is entitled “Tectonic Synthesis of the U.S. Appalachians.” We do not excerpt from that work here or attempt to summarize this synthesis, for it has little, if any, direct bearing on site-specific concerns regarding the Chattahoochee Tunnel. It is noted here as a reference resource.

However, Chapter 29, by David C. Prowell, is entitled “Cretaceous and Cenozoic tectonism on the Atlantic coastal margin.” This information concerning “younger” brittle faulting is pertinent to the present investigation. We saw no evidence for this kind of deformation along the proposed Chattahoochee Tunnel alignment (see Kath and Crawford, 1999). However, excerpts from this paper are presented here to emphasize the need to be alert for any indication of “young” near-surface brittle deformation in the tunnel corridor area.

"Cretaceous and Cenozoic tectonism on the Atlantic coastal margin,” by David Prowell

Introduction

Regional tectonism on the Atlantic coastal margin is expressed in a variety of ways such as uplift, subsidence, tilting of the landmass, geomorphic features, seismicity, and faulting. Of these features, faulting probably is the most definitive evidence of crustal deformation. Major episodes of faulting such as the ductile shearing associated with dynamic metamorphism in the exposed Appalachians and rift faulting associated with the formation of early Mesozoic basins along the Atlantic seaboard have long been a part of the geologic knowledge. However, faulting related to more subtle events, such as the uplift of the Blue Ridge Mountain or post-rift downwarp of the Atlantic continental margin, has received far less attention even though it is an important element of modern geology. Prior to 1970, the eastern United States was generally considered devoid of faults of post-Jurassic age even though evidence of such faulting was available in the late 1800’s. McGee (1888) and Darton (1891) recognized faults in Virginia, Maryland, and Washington, D. C. that involved the juxtaposition of crystalline “basement” and Cretaceous or younger Coastal Plain strata. These observations and the local linearity of the inner margin of the Coastal Plain (Fall Line) lead them to postulate a tectonic control for the updip limit of sedimentation. Confirmation of widespread post-Jurassic tectonism, however, was not readily available and arguments favoring passive warping of the continental edge dominate geologic thought.

In the 1970’s, the construction of nuclear power plants, large dams, and other large structures generated a need to understand Cenozoic tectonism and seismicity in eastern North America. The resulting studies of fault activity in the eastern United States provided evidence of many large, previously unrecognized, Cretaceous and Cenozoic fault zones. For example, Jacobeen (1972), Mixon and Newell (1977), Prowell and O’Connor (1978), Dischinger (1979), Reinhardt and others (1984), and Dischinger...
THOMAS J. CRAWFORD AND RANDY L. KATH

have described faults with vertical displacements of 30 to 76 m and mapped lengths as great as 100 km (Fig. 1).

Early efforts to inventory documented occurrences of post-Jurassic faulting resulted in publications by York and Oliver (1976) and Howard and others (1978), but the detailed information available to these authors was minimal. Recent studies have significantly increased the fault database and a more complete inventory of faults is now available. Prowell (1983) reports more than 130 fault localities east of the Mississippi River and approximately 80 of these localities are along the Atlantic coastal margin. The localities described by Prowell (1983) are based almost entirely on geologic information and most of the data are from field observation of fault exposures. His data shows a predominance of reverse faults along the Atlantic coastal margin that were not predicted by general plate tectonic theory. These observations have generated considerable scientific interest because of the concern over possible seismic hazards and its implications to plate tectonics. The focus of this presentation will be to summarize the more important features of the major post-Jurassic faults in the eastern United States with emphasis on faults in the emerged Atlantic coastal margin.

Regional Distribution of Faults

The onshore faults along the Atlantic coastal margin reported in Prowell (1983) are shown on Plate 8A along with the Coastal Plain, Piedmont, Blue Ridge, and Valley and Ridge physiographic provinces. Several offshore faults reported here from recent geophysical studies (see Behrendt and others, 1981; Hutchinson and Grow, 1985) and the seismic Ramapo fault (see Aggerwal and Sykes, 1978) have also been included on Plate 8A. The recognition of these Cretaceous and younger faults is generally dependent on the observed displacement of geologic units or contacts of an appropriate age range. Hence, most of the observed faults shown on plate 8A are within the Coastal Plain geologic province, where datable, subhorizontal sedimentary horizons are most abundant. The occurrence of datable Cretaceous and Cenozoic materials in the Appalachians, however, is far more limited and undoubtedly is the primary reason for the small number of reported faults in this region. However, close similarity of the fault style recognized in the Appalachians to that in the Atlantic Coastal Plain allows fault characteristics to be extrapolated across this entire region. In addition, seismologic evidence and seismic reflection profiling in conjunction with limited geologic data have been used to assign an age and location to a few faults shown on Plate 8A. These criteria are far less definitive than field observations of faulting but they offer evidence of tectonism in otherwise unevaluated areas.

The abundance of fault data along the inner margin of the Coastal Plain could be taken as an indication of a concentration of tectonic activity, but it may only be a reflection of opportune geologic conditions. Reports of faults along the inner edge of the Coastal Plain typically described crystalline rocks faulted against Cretaceous or younger sediments. Contacts of this sort are far more obvious than those involving the juxtaposition of similar rock types and, therefore, the local geologic conditions may be a major factor in the grouping of faults shown on Plate 8A. Accordingly, areas showing no faults should not be taken to represent a lack of tectonic activity, but rather a lack of sufficient information.

Some of the fault data shown on Plate 8A and in Prowell (1983) were used by Prowell (1976) and Howard and others (1978) to characterize regions of the eastern United States on the basis of fault style. An updated version of their interpretations is shown in Figure 2. The eastern United States is herein subdivided into four tectonic provinces and each can be described by the style of faults within it. These provinces are: (1) the Atlantic Coast province, (2) the Gulf Coast province, (3) the West Georgia Transition province, and (4) the Interior province. A brief description of the fault styles in these provinces provides a framework for understanding the tectonic processes operating during the late Mesozoic and Cenozoic.

Atlantic Coast Province

The Atlantic Coast province is characterized by Cretaceous and younger northeast-trending reverse fault zones and fault systems up to 100 km long. Vertical displacements as great as 76 m have occurred since the Early Cretaceous and progressively smaller offsets have been recognized in rocks spanning the Cenozoic. Although a component of lateral slip has been reported for many reverse faults, dip-slip reverse motion is dominant. The strikes of the fault zones tend to be more northerly in the northern part of the province and more easterly in the southern part of the province, but the strikes are typically within 45 degrees of north. The dips of the fault zones range from 40 to 85 degrees and the dip of
the individual zone may vary depending on the mechanical properties of the rocks in the adjacent fault blocks. Deformation associated with the faulting is extremely brittle in hard rocks and slip surfaces consist of coarse breccias and soft gouge. Coastal Plain strata are typically less sheared and drag folding is well developed. Secondary thermal mineralization is not observed, which indicates that heating and recrystallization (dynamic metamorphism) are not part of this process.

West Georgia Transition Province

In western Georgia and central Florida (?), a zone of transition between the reverse fault and normal fault provinces of the Atlantic and Gulf regions can be recognized. The faults in West Georgia Transition generally are east-west-trending vertical faults or fault zones as much as 30 km long. Vertical displacements in early Tertiary strata are as great as 60 meters and lateral displacement is apparently minimal. These near-vertical faults are commonly flanked by smaller secondary reverse faults (Reinhardt and others, 1984) suggesting that compression is a factor in the deformation. The West Georgia faults, like those of the Atlantic Coast province, exhibit only brittle deformation in crystalline rocks with pronounced drag folding in the adjacent Coastal Plain strata.

OBSERVATIONS, INTERPRETATIONS, AND CONCLUSIONS

A typical concern during geotechnical investigations of tunnels is the occurrence of faults and the perception of associated bad ground and ground water problems. Although the references excerpted in this report do not directly address the geotechnical and hydrogeologic characteristics of faults in general and specifically the Brevard Fault Zone, these references describe the physical nature of the faults observed within the vicinity of the Chattahoochee Tunnel. All of the references cited in this report describe the Brevard Fault Zone as a linear topographic feature characterized by cataclastic rocks that have endured retrograde metamorphism. From published descriptions of the cataclasis and retrogradation associated with faults occurring within this zone, in combination with observations made during the field mapping performed by Kath and Crawford (1999) for this project, comment can be made on the relationship of faults and the potential for bad ground and adverse ground water conditions occurring within the vicinity of the Chattahoochee Tunnel.

Based on the literature and supported by our geologic evaluation, retrograde metamorphism appears to have little or no direct impact on the development of bad ground or adverse ground water conditions along faults within the Brevard Zone. Cataclasism, however, potentially has direct impact on the geotechnical and hydrogeologic character of rock.

Cataclastic rocks are generally formed at great depths below ground surface, ranging between 10 to 15 km in the crust. Physical conditions associated with cataclasism are typically characterized by the reduction in particle size from crushing and grinding along the fault, local recrystallization due high temperature and pressure conditions, and silicification associated with metamorphic fluids. Although the mere occurrence of faults within the Brevard Zone does not necessarily predispose these structural features to having geotechnical and/or hydrogeologic significance with respect to driving a tunnel, the juxtaposition of different lithologies by these faults, is very relevant to the potential enhancement of permeability, differential weathering and development of bad ground and adverse ground water conditions.

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INTRODUCTION
Cobb County Water System (CCWS), located in metropolitan Atlanta, is “tunneling into the future” with construction of the Chattahoochee Tunnel. A large diameter, deep, hard rock tunnel project, the Chattahoochee Tunnel, will relieve the existing Chattahoochee Interceptor. As an environmental project, the Chattahoochee Tunnel will provide needed wastewater transport capacity while greatly reducing the possibility of sanitary sewer overflows into the Chattahoochee River. The Chattahoochee Tunnel will also provide for flow equalization at the existing R.L. Sutton Water Reclamation Facility. This paper presents a one-year update on construction of the Chattahoochee Tunnel.
The Sutton Basin, located in East Cobb, contains a network of sewers totaling more than 500 miles in length, which collects wastewater and conveys it to the R.L. Sutton Water Reclamation Facility (WRF) for treatment, as shown on Figure 2. The Sope Creek Interceptor (30 to 48 inch diameter) and the Chattahoochee Interceptor (42 to 72 inch diameter) form the backbone of the Sutton Basin collection system. The Master Plan indicates that the Sope Creek and Chattahoochee Interceptors are near capacity and do not have adequate capacity for anticipated future flow.

PRELIMINARY ENGINEERING
During the preliminary engineering phase of the project, conventional open-cut sewer options, deep tunnel options, and combination open-cut and tunnel options were considered. A number of specific alternatives were developed and evaluated, including generation of preliminary cost estimates. The deep tunnel option was selected because it will have minimal environmental and community impact. Whereas conventional open-cut sewer construction would have required clear-cutting a wide swath of land extending the entire length of the project, including passing through the Chattahoochee River National Recreation Area and through residential and commercial neighborhoods, the deep tunnel alternative limits surface construction to three shaft and four intake sites. By limiting both the amount of land required for construction and construction activity to these seven sites, the effect of construction on the environment and public will be much less than would have resulted from open-cut sewer construction.

FINAL DESIGN
The starting point for final design of the deep tunnel option was the experience gained from two deep sewer tunnels constructed in the City of Atlanta in the 1980s. These tunnels, known as the Intrenchment Creek Tunnel and the Three Rivers Tunnel, have been in operation for about 20 years and are known to be functioning exceptionally well. Both tunnels were constructed through metamorphic rock in the Piedmont at depths of up to 270 ft below ground surface, using tunnel boring machines (TBMs). The Intrenchment Creek Tunnel is a combined sewer overflow tunnel, about 9,300 ft long and 26 ft in diameter. The Three Rivers Tunnel is a secondary effluent tunnel, about 7 miles long and 10 ft in diameter.

Key features of the Atlanta tunnels that formed the basis of design of the Chattahoochee Tunnel are:

- The rock through which the tunnels were constructed was excellent for tunneling.
- Excavation was successfully performed using TBMs.
- Most of the excavated length of the tunnels was unsupported, i.e., no initial supports were installed in the rock.
- Areas of fractured rock, where encountered, were supported either by rock bolts with or without wire mesh, or steel ribs.
- Groundwater inflow was generally quite low, although one large inflow did occur.
- The tunnels were lined with cast-in-place concrete only in areas of fractured rock or significant groundwater inflow.

Final design of the Chattahoochee Tunnel specifies a tunnel that will be nearly 50,000 ft long, 100 to 375 ft below ground surface, with an excavated diameter of 18 ft and a finished diameter of 16 ft in the concrete-lined sections. A plan showing the alignment of the tunnel and the major structures along its length is shown in Figure 3. The project includes excavation of the 100 ft diameter, 170 ft deep Pump Station Shaft at the R.L. Sutton WRF. In addition, two 32 ft diameter construction shafts will be developed primarily for staging TBM construction. The southern portion of the tunnel, known as the South Drive, will be staged from the 180 ft deep Elizabeth Lane Construction Shaft. The North Drive will be

Figure 3. Chattahoochee Tunnel Project.
staged from the 230 ft deep Circle 75 Parkway Construction Shaft.

At the northern end of the tunnel, flow from the Sope Creek and Sewell Mill Interceptors will be dropped into the tunnel at the Indian Hills Intake Structure. Two other intakes are located along the tunnel alignment, one at the Rottenwood Creek Interceptor and another at the Little Nancy Creek Interceptor. A fourth intake diverts flow from the Chattahoochee Interceptor to the Pump Station through the Connector Tunnel. The Chattahoochee Interceptor Intake and the Connector Tunnel are located entirely within the property limits of the Sutton WRF.

Final design required the South Drive and North Drive tunnels to be excavated using TBMs. The section of main tunnel extending from the Pump Station Shaft to the Elizabeth Lane Construction Shaft and the Connector Tunnel are required to be excavated using drill and blast techniques. Reinforced concrete diaphragm walls are specified to support soil excavation at the pump station and construction shafts. The rock extending from the diaphragm walls to the bottom of the shafts will be excavated using drilling and blasting. The drop and vent pipes at the intake structures will be constructed using raise boring techniques.

SUBSURFACE INVESTIGATION
The Chattahoochee Tunnel is located in the Piedmont region of the southeastern United States. In the Atlanta area, the geology of the Piedmont consists of metamorphic rocks that have been intruded by granitic rocks in some places. These crystalline rocks were formed before and during the building of the Appalachian Mountains more than 200 million years ago. Since that time, they have undergone intense weathering, erosion and some regional uplifting.

An important characteristic of the Piedmont is the thick layer of residual soil that slowly grades downward into bedrock. This characteristic makes it convenient to divide the ground into three zones: the soil zone, the transition zone, and the bedrock zone. The Chattahoochee Tunnel area is also characterized by abundant joint sets, which become tighter and less abundant with depth.

The subsurface investigation for the Chattahoochee Tunnel was designed to investigate soil, rock and joint conditions. The major elements of this investigation consisted of the following:

- Geologic mapping of rock outcrops along the tunnel alignment.
- Vertical core borings, including soil and rock sampling.
- Angled rock core borings.
- Packer permeability testing in most of the core borings.
- Air rotary borings
- Laboratory testing for rock mineralogy, strength, and abrasivity.
A profile of subsurface conditions along the tunnel alignment is shown in Figure 4. With regard to boreability of the TBMs, the rocks along the tunnel alignment are strong, hard and abrasive. The rocks contain significant amounts of quartz and garnet, which will be abrasive to the disk cutters on the TBMs.

With regard to support of tunnel excavation, the results of the subsurface investigation indicate that the majority of the rock at tunnel depth is considered good to very good, according to the Rock Mass Rating System (Bieniawski, 1981). As a result, the initial support system will predominantly consist of rock dowels. In areas of more fractured rock, steel rib support will be required.

Low to moderate amounts of groundwater are expected during tunnel excavation. Based on statistical evaluation of the packer permeability test data, projections for heading inflows and long-term inflows were made.

**BIDDING**

The bidding phase of the project began with pre-qualification of prospective contractors. Requirements for pre-qualification included:

- Submission of an Application for Pre-qualification, which lists previous work experience, current work load, personnel and equipment lists, safety record, bonding capacity, financial statement, references, and prior and current litigation.
- Satisfactory completion within the last five years of at least one major TBM rock tunneling project consisting of similar scope to this project and similar to the estimated contract value of this project.
- Six key staff personnel, including Principal-in-Charge, Contract Administrator, Safety Manager, Project Manager, Project Superintendent and Safety Engineer shall have had at least 10 years’ experience in hard rock, TBM tunneling work.
- Current assets minus current liabilities of at least $1.5 million.

Of the six pre-qualification applications received, four of the bidding entities were considered pre-qualified and permitted to bid the project.

After a 10-week bid period, bids were received by Cobb County on March 23, 2000. Three bids were received, the lowest of which totaled $113,581,000. The other two bids were in the range of $121 to $124 million. Contract award was made on May 1, 2000, and notice-to-proceed was issued on June 28, 2000.

**CONSTRUCTION**

The construction period for the Chattahoochee Tunnel extends for 44 months, resulting in a completion date of February 28, 2004. In addition, an interim milestone occurs 18 months into construction, at which time construction must be complete on the Pump Station Shaft, the Chattahoochee Interceptor Intake, the Connector Tunnel and the main tunnel extending from the Pump Station Shaft to the Elizabeth Lane Construction Shaft.

After 13 months of the 44-month construction period, excavation of the Pump Station Shaft, the Elizabeth Lane Construction Shaft, and the Circle 75 Parkway Construction Shaft has been completed. An aerial
photograph of the Pump Station Shaft site is presented in Figure 5. The drill and blast main tunnel has been excavated a distance of 859 ft from the Pump Station Shaft and the Connector Tunnel is 759 ft from its intersection with the Main Tunnel. At the Elizabeth Lane site, the contractor has excavated a starter tunnel 333 ft ahead of shaft centerline and a tail tunnel 107 ft behind shaft centerline. The starter and tail tunnels were then used to accommodate set-up and launch of the TBM. The TBM for the South Drive began excavation on August 1, 2001. The TBM for the North Drive is currently being retrofitted at the manufacturing facility. A photograph of the TBM is shown in Figure 6.

According to the contractor’s latest schedule update, excavation of the 22,156 ft South Drive, which includes areas of probe hole drilling and pre-excavation grouting, is expected to be complete in mid December 2002. The TBM for the North Drive will be launched from the Circle 75 Parkway Construction Shaft in mid October 2001. Excavation of the 25,652 ft North Drive is expected to be complete in late August 2002.

SUMMARY
In general, the project has proceeded as expected to date. The quality of the rock encountered has been as good as anticipated and groundwater inflows have been minimal.

REFERENCE
INTRODUCTION

Petrologic Solutions, Inc. (Petrologic Solutions) was retained by Jordan, Jones, and Goulding, Inc. (JJG) to perform an evaluation of the geologic conditions that may impact construction of the Chattahoochee Tunnel (CT) in Cobb County, Georgia. The CT, location shown in Figure 1, was proposed to be constructed as a 16-foot diameter tunnel excavated below ground surface. The alignment of the CT crosses numerous surface drainages, is locally close to the Chattahoochee River, and crosses the Brevard Zone, as shown in Figure 2. Technical considerations related to the proposed tunnel, such as distribution of lithologic units, geologic structures, depth of weathering, and the potential for groundwater movement have been evaluated and are presented herein.

For this evaluation, a desk study was conducted to collect existing information on geologic conditions within the vicinity of the CT and a lineament analysis was performed. Specifically, technical information that could provide information on depth of weathering and the potential for significant groundwater movement was addressed. The premise of this evaluation is that differential weathering occurs along discontinuities (compositional layering, joints, shear planes, random fractures, faults...) that have higher relative permeability than the general rock. The weathered rocks are typically softer and more erodible than their unweathered parent rock. Erosion and weathering of material along discontinuities frequently results in linear topographic features, which are referred to as lineaments. Ground water in igneous and metamorphic rocks generally moves along discontinuities in the bedrock, enhancing the differential weathering processes.
A geologic literature review, detailed geologic mapping, and topographic lineament analysis were conducted to identify geologic and topographic features, which could be used as a guide for predicting probable groundwater conditions. Figure 2 shows the area included in the literature review investigation.

The main focus of the geologic literature review was to characterize the different formations and rock types along the CT alignment. The main focus of the lineament analysis program was to characterize and describe topographic linears within the CT corridor (as defined by JJJ). The results of the geologic literature review and lineament analysis are presented herein.

REGIONAL GEOLOGIC SETTING

Physiography

The CT site is located in the Piedmont/Blue Ridge geologic province, which contains the oldest rocks in the Southeastern United States. Since their origin, some 400 to 600 million years ago (Ma), these late Precambrian and early Paleozoic rocks have undergone repeated cycles of igneous intrusions and extrusions, metamorphism, folding, faulting, shearing, and silicification. The latest regional metamorphism and associated deformation has been attributed to the collision of the North America plate with the Eurasian plate approximately 200 to 230 Ma. More recent deformation and emplacement of mafic dikes is associated with the rifting of the North American craton during the Mesozoic and Cenozoic Eras.
DETAILED GEOLOGIC MAPPING ALONG THE CHATTAHOOCHEE TUNNEL

**General**

Much of the information provided in this section is taken from available literature (Higgins, 1968; McConnell and Abrams, 1984; Higgins and others, 1997 (in press); Crawford, personnel communication, 1997; and Higgins, personnel communication, 1997).

Any proposed alignment from Indian Hills to the R.L. Sutton Waste Water Treatment Plant (WWTP) will cross various rock types and structures that are a part of the Brevard Zone (Figure 2). The Brevard Zone is a major regional zone of deformation in the Piedmont/Blue Ridge that extends from Alabama to Virginia. In general, both the rock types and major structural features in the Brevard Zone trend northeast-southwest. The lithologic units consist of various types of gneiss, schist, quartzite, and amphibolite/hornblende gneiss. Structural features include folds, faults, foliation, shear foliation, joints, and other discontinuities.

**Stratigraphy Based on Previous Work**

Rock types of the Brevard Zone along the Chattahoochee River from Indian Hills to the R.L. Sutton WWTP include: an unnamed Granitic Gneiss formation (PZgn), Frolona Formation (OZsf), Ropes Creek Metabasalt (OZr), Mixed Unit (OZb), Powers Ferry Formation (OZpf), Frolona Formation (OZfs, Factory Shoals Member), Powers Ferry Formation (OZpf), Frolona Formation (OZfs, Factory Shoals Member), Long Island Creek Gneiss (Oli), and Sandy Springs Group (CSssb). Rocks within these various formations and groups have been intensely deformed, sheared, altered, and are generally repeated because of movement along faults both within and outside of the Brevard Zone. The general description of each unit is given below and the aerial distribution of each unit is shown in a generalized geologic map, Figure 2.

**Unnamed Granitic Gneiss**

An unnamed granitic gneiss unit (PZgn) consists dominantly of a muscovite-biotite-potassium-feldspar-quartz-plagioclase gneiss. The high feldspar content of the gneiss causes this formation to weather deeply. The weathered by-product is usually a silty-rich saprolite/soil that would generally be classified using the Unified Soils Classification System (USCS) as an ML.

**Frolona Formation**

The Frolona Formation (OZsf) consists of graphitic schist, muscovite schist, quartzose schist, and quartzite. The graphitic schist units are fine- to medium-grained and dark-gray to nearly black; metaconglomerates are associated with this formation.

**Ropes Creek Metabasalt**

The Ropes Creek Metabasalt (OZr) is a garnet-bearing hornblende-plagioclase amphibolite-hornblende gneiss similar to amphibolite-hornblende gneiss in the Powers Ferry Formation; however, the Ropes Creek is generally finer-grained. Where the Ropes Creek Metabasalt is fresh, it is generally dark-green to greenish-black. Because of the fine-grained nature of this unit, the Ropes Creek Metabasalt is typically less weathered than the Powers Ferry Formation.

One of the characteristic features of the Ropes Creek Metabasalt is that it weathers to a dark-red clay-rich soil. This soil would generally be classified using the USCS as a CL or CH.

**A Mixed Unit**

The Mixed Unit (OZb) has not been formally assigned to a formation. This unit consists of medium- to coarse-grained muscovite schist, graphitic schist, biotite gneiss, and plagioclase-hornblende amphibolite-hornblende gneiss. This unit locally contains pods or lenses of chlorite-hornblende-actinolite schist. Weathering in this unit is highly variable.

**Powers Ferry Formation**

The Powers Ferry Formation (Ozpf) consists dominantly of biotite gneiss interlayered with muscovite schist. Locally, thin lenticular-shaped pods of hornblende-plagioclase amphibolite-hornblende gneiss are present. The gneiss units of the Powers Ferry Formation are generally light gray, garnet-bearing and biotite rich. The high feldspar content of both the schist and gneiss causes this formation to weather deeply. The weathered by-product is generally a silty-rich saprolite/soil that would generally be classified using the USCS as an ML.
Frolona Formation (Factory Shoals Member)-
The Frolona Formation, Factory Shoals Member (OZfs) consists of minor graphitic schist, muscovite-biotite-quartz schist, muscovite-biotite-quartz-feldspar gneiss, and quartzose schist.

Long Island Creek Gneiss-
The Long Island Creek Gneiss (Oli) is dominantly a light-gray to gray, epidote-bearing, biotite-muscovite-quartz-feldspar gneiss. Because of the high feldspar content of this gneiss, it is deeply weathered. The soils derived from this unit are a characteristic yellow color and are generally classified as CL or ML.

Sandy Springs Group-
The Sandy Springs Group (CSssb) consists of dominantly chlorite and sericite (fine-grained muscovite) schist with a characteristic button texture. The button texture is due to multiple shear planes associated with movement along the Brevard Zone. Because of the high quartz content, the Sandy Springs Group lithologies are only moderately weathered.

DETAILED SITE GEOLOGIC SETTING AND STRUCTURAL ANALYSIS

General Site Geology
Geologic mapping of the site was performed by Randy L. Kath and Thomas J. Crawford, using the Atlanta Northwest and Sandy Springs Quadrangle maps produced by the United States Geologic Survey (USGS) as base maps. These maps are at 1:24,000 scale and are a 7½-minute series topographic map. The main area of review was the southern half of the Sandy Springs quadrangle and the northern half of the Atlanta Northwest quadrangle. The geologic map, presented as Figure 3a, 3b, and 3c, is based on detailed geologic mapping along and adjacent to the alignment corridor.

Generally, the rock types likely to be encountered along tunnel alignments proposed in this area will consist of biotite gneiss, granitic biotite gneiss, muscovite schist, quartzose schist, quartzite, amphibolite-hornblende gneiss, and ultramafic rocks. When unweathered, these rocks types are strong and of high quality for tunneling. However, the strength and quality of the rock and the mass permeability are strongly related to the degree of weathering. Thus, an evaluation of the degree of weathering at tunnel-level is important for assessing potential tunnel excavation methods, potential problems and support requirements.

Because these rock types have different mineralogy, texture, and chemistry they will weather differently. In general, the overall degree of weathering, from least weathered to most weathered, is: quartzite, quartzose muscovite schist, muscovite schist, ultramafic, amphibolite-hornblende gneiss, and biotite gneiss. However, because of structural attitudes, zones of deeply-weathered rock may be present at depth, underlying units that are very resistant to weathering.

The overall depth of weathering in the Atlanta area is generally about 30 to 60 feet, but weathering along discontinuities may extend to depths greater than 120 feet. Depth of weathering can vary significantly over short horizontal distances.

Soil Development
The parent rocks of soils in the region are comprised primarily of quartz, feldspars, muscovite mica, hornblende, biotite mica, and a wide variety of accessory minerals such as magnetite and garnet. Because of the crystalline nature of the parent rock, chemical decomposition initially occurs along the boundaries of individual mineral crystals. The derived soil occupies the same general position previously occupied by crystals in the original rock. As a result, partially weathered rock typically resembles the parent rock in appearance. However, strength and permeability characteristics are more similar to very dense silty sand or sand (SM or SP), reflecting the grain size of the parent rock. With further weathering, the individual crystals other than quartz and muscovite are altered and the mass typically becomes a micaceous silty sand (SM) or micaceous sandy silt (ML). In this stage, the original texture of the parent rock is still apparent, but the original crystalline structure is no longer preserved. Depending upon the composition of the
DETAILED GEOLOGIC MAP ALONG THE CHATTAHOOCHEE TUNNEL ALIGNMENT

MATCH LINE A

NOTES:
1) SEE SHEET 3c FOR EXPLANATION OF SYMBOLS AND LITHOLOGIC UNITS
2) BASE MAP TAKEN FROM THE SANDY SPRINGS (1983) AND NORTHWEST ATLANTA (1983), U.S. GEOLOGICAL SURVEY, 7.5 MINUTE SERIES (TOPOGRAPHIC)
3) GEOLOGIC MAPPING BASE 1:24000
DETAILED GEOLOGIC MAP ALONG THE CHATTAHOOCHEE TUNNEL ALIGNMENT

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3) GEOLOGIC MAPPING BASE 1:24000
Geologic Legend

3c mafics yield a hard, tough saprolite with well-developed boxwork; and pegmatites are present in residuum as resistant boulders.

RLK

weathers deeply to a soft, feldspathic residuum, except for the coarse-grained mafic and ultramafic bodies and the pegamites. The coarse-grained TJC N.T.S. feet to a few hundred feet in their longest dimension, and muscovite-quartz-feldspar pegmatites as much as 8 to 12 feet thick. This rock unit 5/24/99 The remaining part of this lithologic unit consists of small medium- to coarse-grained mafic and ultramafic bodies, apparently ovoid and several feet to a few hundred feet in their longest dimension.

EXPLANATION FOR GEOLOGIC MAP

Biotite-quartz-feldspar gneiss, fine- to medium-grained, schistose in part; biotite-hornblende-feldspar gneiss, fine- to medium-grained, and garnet-muscovite-biotite-quartz-feldspar gneiss, fine- to medium-grained, and garnet (common to abundant)-feldspar-quartz-schist, coarse-grained, button texture, with abundant fine disseminated black opaques; interlayered on a scale of feet and 10's of feet. Foliation orientation is highly variable over short distances. Outcrop width along the tunnel alignment is approximately 400 feet.

Garnet-biotite-muscovite-quartz schists, coarse-grained, with thickly disseminated fine black opaques; muscovite is generally coarser-grained than biotite; sheared, with a button texture. Joints are poorly developed and scarce; shallow-weathering. Outcrop width along the tunnel alignment is approximately 800 feet.

Garnet-biotite-quartz-muscovite schist, coarse-grained, with tourmaline and thickly disseminated fine black opaques; sheared, with a button texture. Outcrop width along the tunnel alignment is approximately 1,000 feet.

Garnet-kyanite-feldspar-muscovite-biotite-quartz schist, fine- to coarse-grained; very quartzose, in part. Garnet-kyanite-muscovite-biotite-quartz-gneiss, fine- to medium-grained, with a poorly developed foliation. Shear foliation is commonly developed. Muscovite is present where this gneiss is sheared. Shear foliation is commonly developed. Biotite-quartz-feldspar granite, medium- to coarse-grained, equigranular, massive, without foliation or with only a poorly developed foliation, are scattered in thick residuum often contains large bouldery masses of relatively fresh rock. Small, apparently ovoid bodies of biotite-quartz-feldspar granite, medium- to coarse-grained, equigranular, massive, without foliation or with only a poorly developed foliation.
original rock, muscovite flakes, rather than quartz grains, may comprise the majority of the sand-size particles. The material resulting from this stage of weathering is termed saprolite.

In the most advanced stages of chemical weathering, the material is changed into a red or reddish-brown silty clay (CL or CH) or clayey silt (ML or MH) with a sandy fraction directly related to the quartz content of the parent rock. In this weathered stage, the banding and crystalline structure of the parent rocks are lost.

Lithologic/Rock Units

In these descriptions of the mineralogy of rock units, the minerals are listed in order of increasing abundance. For purposes of description, each lithologic unit was assigned a number. Rock Unit 1 is at the southern end the alignment (R.L. Sutton Pump Shaft), and numbers are in sequence northward along the alignment, with Rock Unit 16 being at the northern end (Indian Hills Construction and Intake Shaft; see Figure 3a and 3b).

Rock Unit 1A

Mylonite, composed of sericite, quartz, and feldspar; extremely fine-grained; foliation is poorly developed and very contorted; dark gray, light gray, and white in outcrop; yields uniform fine clayey residuum, buff to pale red.

The uniform fine grain size, uniform composition, and poorly developed contorted foliation all inhibit weathering; however, the abundance of feldspar enhances weathering. Combined, these characteristics result in a generally moderate and uniform depth of weathering.

Rock Unit 1B

Mylonitized granite, composed of muscovite, quartz, and feldspar; much of the feldspar is pink and coarse-grained. Shearing was pervasive and produced a well-developed shear foliation. Reduction in grain size was not as extreme as in Rock Unit 1A; light colored; cream buff, pink.

Where shear foliation is absent or poorly developed, this rock unit is massive, with few discontinuities, and shallow weathering. The development of a shear foliation in parts of the granite has provided discontinuities which weakened the rock and allowed more rapid weathering, resulting in tabular zones of deeper, more intense weathering.

Rock Unit 1C

Mylonite, mylonitic button schist and mylonitic biotite gneiss; all interlayered on a scale of inches, feet, and 10’s of feet. The mylonite is composed of sericite, quartz, and feldspar, extremely fine-grained, with a poorly developed foliation. The mylonitic button schist is composed primarily of fine sericite, muscovite, quartz, and feldspar; with medium- to coarse-grained muscovite forming distinctive “eyes”; there is a well-developed shear foliation. The mylonitic biotite gneiss is composed primarily of biotite, quartz, and feldspar, very fine-grained; with a well-developed shear foliation.

Even though there are considerable differences in the mineralogy of these interlayered lithologies, the overall fine grain size seems to be the dominant control on weathering. As in Rock Unit 1A, this results in generally moderate and uniform depths of weathering.

Rock Unit 2

Sphene-epidote-biotite-quartz-feldspar gneiss, medium- to coarse-grained; very felsic; yields light-colored soil; foliation is moderately well-developed.

Near its contact with Unit 1 and for several hundred feet to the northwest, this gneiss is extremely sheared, with a very close-spaced and well-developed shear foliation. Shearing decreases toward the northwest.

Rock Unit 2 is massive and uniform, with general shallow to moderate weathering. Along shear zones and joints weathering has proceeded to greater depth.
Rock Unit 3
Between Rock Unit 2 and Rock Unit 4, there is a mixture of lithologies which changes character along strike and, probably, down-dip.

Within this sequence are:
1) Garnet-kyanite-feldspar-muscovite-biotite-quartz schist, fine- to coarse-grained; very quartzose, in part.
2) Garnet-kyanite-muscovite-biotite-quartz-feldspar gneiss, fine- to coarse-grained; schistose in part.
3) Quartzite; medium-grained and clean in part; also fine- to coarse-grained and micaceous and/or feldspathic.
4) Amphibolite/hornblende gneiss, fine- to medium-grained.
5) Ultramafic - coarse grained pyroxene and amphibole; massive; apparently as small ovoid bodies several 10’s of feet to a few 100 feet in their longest dimension.

Pegmatites and pegmatitic layers, lenses, and pods are common throughout. The quartzite was mapped separately, where feasible; grades into quartzose schist. Foliation parallel to compositional layering is well developed in Unit 3; shearing is common.

The great differences in mineral composition, texture, and discontinuities in this Rock Unit have caused considerable internal differences in weathering depths. However, the general high content of quartz and muscovite has restricted the overall depth of weathering.

The quartzites, quartzose muscovite schists, and coarse-grained ultramafics are the least weathered lithologies in this Unit; the feldspar- and biotite-rich gneisses and schists the most weathered.

The contrasts in weathering depths make this Unit potentially troublesome.

Rock Unit 4
Biotite-quartz-feldspar gneiss; quartz and feldspar are medium- to coarse-grained; biotite is fine- to medium-grained. Muscovite is present where this gneiss is sheared. Shear foliation is commonly developed. This gneiss is very felsic.

The high feldspar content, combined with the dominant mica being biotite rather than muscovite, enhances the weathering of Rock Unit 4. However, its massiveness and uniformity inhibit weathering. Consequently, weathering is rather uniform and of moderate depth except in areas of joint concentrations.

Rock Unit 5
Rock Unit 5 is a schist/gneiss/quartzite unit, the same as Rock Unit 3. Diverse weathering characteristics of this sequence will be very similar to those of Rock Unit 3.

Rock Unit 6
Rock Unit 6 consists of garnet (small, scarce)-biotite-muscovite-quartz-feldspar gneiss, fine- to coarse-grained; interlayered with garnet-feldspar-biotite-muscovite-quartz schist, medium- to coarse-grained; all gradations from well-developed gneiss to well-developed schist (gneiss, schistose gneiss, gneissic schist, and schist); thin zones contain abundant garnets. This unit is well foliated; weathering produces a slabby outcrop and slabby residuum.

Quartz veins and pegmatites are present, but not abundant. Along the railroad west of the tunnel alignment, this unit contains muscovite-quartz schist and fine- to medium-grained micaceous and feldspathic quartzite, intensely sheared.

Rock Unit 6 has well-developed compositional layering and foliation; the more gneissic parts have well-developed joint sets; and the schists and quartzites are feldspathic, in part. This combination results in pronounced differential weathering within Rock Unit 6, and enhances the probability for significant groundwater.

Rock Unit 7
Rock Unit 7 is thin, approximately 600 feet in outcrop width along the tunnel alignment, and consists of:
1) Quartzite and micaceous quartzite, fine- to medium-grained, intensely sheared; structurally overlain by:
2) Kyanite-garnet-feldspar-biotite-muscovite-quartz schist, coarse-grained, with feldspar “eyes”, and abundant concordant pegmatitic pods, lenses, and layers;
3) This schist is structurally overlain by another schist, with fewer and smaller garnets, less biotite and muscovite, and more quartz; which, in turn, is structurally overlain by:

4) A garnet (small, scarce)-biotite-muscovite-feldspar-quartz gneiss, fine-grained, well foliated and slabby; appears to have been intensely sheared and silicified.

The dominance of muscovite and quartz in this thin rock unit suggests that it will not be deeply weathered. However, it has deformed brittlely, and the abundance of joints and joint sets enhance porosity and permeability.

**Rock Unit 8**

Garnet (small, minor)-muscovite-biotite-quartz-feldspar gneiss, fine- to medium-grained, schistose in part; interlayered with garnet (small, minor)-biotite-feldspar-quartz-muscovite schist, medium- to coarse-grained; some garnet-rich zones; all laced with concordant and discordant pegmatite pods, lenses, and layers up to 10 feet thick; foliation wraps around pegmatite pods/lenses.

Well-developed compositional layering/foliation, two well-developed joint sets, high feldspar content, and the abundance of large pegmatites control differential weathering which will be quite deep in places. In a favorable topographic setting, groundwater potential is considerable.

**Rock Unit 9**

Rock Unit 9 is thin, approximately 300 feet in outcrop width along the tunnel alignment, and consists of:

1) Kyanite-garnet-biotite-quartz-muscovite schist, coarse-grained, sheared, with abundant pegmatite pods and lenses; structurally overlain and underlain by:

2) Quartzite, fine- to coarse-grained, in layers 1- to 8-inches thick. The quartzite structurally overlying the schist appears to be several 10’s of feet thick; while the quartzite underlying the schist appears to be less than 10 feet thick.

Weathering and groundwater potential of this rock unit is similar to that of Rock Unit 7. The dominance of muscovite and quartz suggests that it will not be deeply weathered. However, it has deformed brittlely, and the abundance of joints and joint sets enhance porosity and permeability.

**Rock Unit 10**

Muscovite-biotite-quartz-feldspar gneiss, with scattered small garnets, fine- to coarse-grained; discordant pegmatites and pegmatitic zones are common; quartz veins are small and scattered.

Differences in grain size, development of foliation, and presence and abundance of joints cause differential weathering in Rock Unit 10. Favorable topographic and structural settings could produce considerable groundwater.

**Rock Unit 11**

Garnet-biotite-quartz-muscovite schist, coarse-grained, with tourmaline and thickly disseminated fine black opaque; sheared, button texture. Outcrop width along the tunnel alignment is approximately 1,000 feet.

Dominance of quartz and muscovite and scarcity of joints suggest shallow weathering, and little potential for groundwater.

**Rock Unit 12**

Amphibolite-hornblende gneiss, thinly laminated, fine- to medium-grained, hornblende and plagioclase; and chlorite-actinolite schist, very fine-grained. Joints are close-spaced and abundant. Outcrop width along the tunnel alignment is approximately 600 feet.

The amphibolite/hornblende gneiss of Rock Unit 12, and the amphibolite/hornblende gneiss interlayered with schist of Rock Unit 13 have the potential for large groundwater yields. Their mineralogy and abundance of joints make them susceptible to weathering. In addition, their structural position between underlying and overlying muscovite- and quartz-rich schists make them a relatively easy surface-water and groundwater pathway.

**Rock Unit 13**

Hornblende gneiss/amphibolite, thinly laminated fine- to medium-grained hornblende and plagioclase; and garnet-biotite-feldspar-quartz-muscovite schist, coarse-grained, button texture, with abundant fine disseminated black opaques; interlayered on a scale
of feet and 10’s of feet. Foliation orientation is highly variable over short distances. Outcrop width along the tunnel alignment is approximately 800 feet.

Weathering/groundwater - see comments under Rock Unit 12.

**Rock Unit 14**

Garnet-biotite-muscovite-quartz schist, coarse-grained, with thickly disseminated fine black opaques; muscovite is generally coarser-grained than biotite; sheared, button texture. Joints are poorly developed and scarce; shallow-weathering. Outcrop width along the tunnel alignment is approximately 400 feet.

An abundance of muscovite and quartz combined with poor joint development has caused depth of weathering to be shallow and groundwater potential to be low.

**Rock Unit 15**

Garnet-muscovite-biotite-quartz-feldspar gneiss, fine- to medium-grained, and garnet (common to abundant)-feldspar-quartz-muscovite-biotite schist, medium- to coarse-grained, interlayered; and all extensively pegmatized with coarse-grained muscovite-quartz-feldspar. Micas in the schist are often coarse-grained and in part oriented across the compositional layering creating a “tough” rock which resists breaking. This rock unit is very non-uniform. It weathers unevenly, and often in non-planar directions. Where compositional layering and foliation are well developed, differential weathering produces a slabby outcrop; the thickness of weathering residuum varies from thin to thick over short distances; and thick residuum often contains large bouldery masses of relatively fresh rock. Small, apparently ovoid bodies of biotite-quartz-feldspar granite, medium- to coarse-grained, equigranular, massive, without foliation or with only a poorly developed foliation, are scattered in this unit.

Depth of weathering and groundwater potential are quite variable. Favorable structural and topographic positions will yield large volumes of groundwater.

**Rock Unit 16**

Biotite-quartz-feldspar gneiss, fine- to medium-grained, schistose in part; biotite-hornblende-feldspar gneiss, fine- to medium-grained; and amphibolite, fine- to medium-grained; all are interlayered or intermixed. Together, and in approximately equal parts, these three lithologies make up greater than 90 percent of this rock unit. The rock weathers to a yellow-brown, pink, or brownish gray saprolite/residuum. The remaining part of this lithologic unit consists of small medium- to coarse-grained mafic and ultramafic bodies, apparently ovoid and several feet to a few hundred feet in their longest dimension, and muscovite-quartz-feldspar pegmatites as much as 8 to 12 feet thick. This rock unit weathers deeply to a soft, feldspathic residuum, except for the coarse-grained mafic and ultramafic bodies and the pegamites. The coarse-grained mafics yield a hard, tough saprolite with well-developed boxwork; and pegmatites are present in residuum as resistant boulders.

Like Rock Unit 15, this rock unit contains small, apparently ovoid, bodies of biotite-quartz-feldspar granite, medium- to coarse-grained, equigranular; massive, without foliation or with only a poorly developed foliation. Only one small body was noted along the tunnel alignment in this unit; there may be others.

The biotite and feldspar content of Rock Unit 16 has allowed deep weathering and lots of groundwater storage. The variability of its lithologies and the pervasive large pegmatites enhance the potential for groundwater. Expect large volumes at sites with favorable structural and topographic settings.

There should be little water in the small granite bodies of Rock Units 15 and 16.

**Structure**

The structures within the Brevard Zone are complex and have been debated in the geologic literature for many years. Two prominent features of the Brevard Zone are a granulation of the rocks and shear-induced foliation (shear foliation). Generally, the shear foliation trends northeasterly and dips at moderate to steep angles to the southeast. This foliation nearly parallels geologic contacts on a local scale; however, on a regional scale, the foliation may be slightly oblique to geologic contacts.
Foliation
One of the most prominent features of the Brevard Zone is the presence of a well-developed shear foliation. The shear foliation is generally parallel to compositional layering or transposed compositional layering. Equal-area-stereonet analysis of the foliation measurements indicates a consistent southeast dip between 20 and 55 degrees, Figure 4. The maximum concentration of poles to foliation planes illustrated in Figure 4, represents foliation planes trending N52E, inclined 35 degrees to the southeast.

Faults
Other prominent features of the Brevard Zone are faults. Major faults within the Brevard Zone are interpreted to be sub-parallel or parallel to foliation (Figure 2 and Figures 3a and 3b). Between Indian Hills and the R.L. Sutton WWTP two of these major faults are crossed by the alignment (refer to Figure 2).

The northern-most fault is approximately parallel to the northern bank of the Chattahoochee River near Sope Creek. This fault, the Frolona Fault, is expected to be encountered by the proposed tunnel. Another major fault in this area is the Long Island Fault. The Long Island Fault separates schist and gneiss of the Frolona Formation from gneiss of the Long Island Creek Formation and is crossed near the southern end of the tunnel alignment. Many, if not all, of the contacts between lithologic rock units are probably fault contacts.

Deformation within the Brevard Zone was dominated by relatively high-pressure crushing and shearing. As a result of these stresses, the shear foliations and faults were produced. In addition, the crushing reduced the grain size of the rocks, which generally reduced permeability. Further, silica-rich metamorphic fluids associated with this crushing tended to heal the fractures. Because of this healing, the permeability along the zones of intense shearing and silicification is expected to be very low and the rocks along these zones are expected to be strong and of high quality for tunneling.

Joints
Joints within the Brevard Zone are common and persistent in most of the rock types. The joints are generally spaced on the order of a few inches to a few feet apart; however, more massive portions of the gneiss and quartzite may have a wider joint spacing.

Three major and one minor joint set were recorded during the detailed geologic mapping. Equal area stereonet analysis of all joints measured in all lithologies is presented in Figure 5.

The three major joint sets are (quadrant and azimuth, right hand rule):
1) N81W 70NE (279/70),
2) N16E 67NW (196/67), and
3) N56W 89SW (126/89).
The one minor joint set is:
4) N52E 68NW (232/68).
Locally, some of the joints contain clay infillings; however, most of the joints do not contain any infillings in surface exposures. The plane-surface morphology of each joint was noted in the field descriptions. Most of the joints are planar and smooth with little to no evidence of high fluid flow.
LINEAMENT ANALYSIS

General

Lineament analyses were conducted on 1:24,000 topographic maps. Linear features or linear groups of features were identified and traced on overlays of the maps. Lineaments arise from a number of sources. Many lineaments observed on the small-scale imagery or maps are related to fence, property, and section lines. However, many lineaments are related to local and regional geologic anomalies. Rectilinear segments of streams may be associated with local weakness in the underlying bedrock related to persistent joint sets. Faults tend to be long linear features that are often difficult to detect at ground surface, but generally form photographic and topographic lineaments.

Approach and Methodology

Topographic Maps

Lineament analysis was conducted on 1:24,000 USGS quadrangle maps along the CT corridor. Topographic map interpretation was conducted by Petrologic Solutions from May 22 to May 28, 1997.

On topographic maps, linear geomorphic features are shown by topography or topographic features which are laterally continuous. Any of the linear geomorphic features which cross-cut topography are interpreted to represent a significant lineation. For example, many significant linear features are expressed by linear segments of streams where the extension of the feature, along strike, is observed crosscutting ridges or other topographic features.

Topographic maps facilitated identification of regional linear geomorphic landforms combined with a rectilinear stream analysis. All linears noted on the topographic sheets constitute through-going, persistent, linear or curvilinear features. The features are interpreted as representing stratigraphic and/or structural zones of weaknesses.
Discussion of Lineaments

Topographic Maps

Lineaments observed on the 1:24,000 scale topographic maps are presented in Attachment B and summarized in Figure 6. This Figure 6 illustrates the persistence and orientation of topographic linear or curvilinear features. The rose diagram illustrates a nearly bi-modal distribution of major lineaments. The bi-modal distribution trends between N50°E to N60°E and N30°W to N40°W. One minor set is also shown on this diagram: N70°W to N80°W.

REFERENCES


Crawford, T.J., 1997, Personnel Communication regarding the Vinings, Georgia area.


CHARACTERIZATION OF VEINS AND ASSOCIATED ALTERATION IN A BEDROCK CORE TAKEN FROM THE BREVARD ZONE, COBB COUNTY, GEORGIA

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INTRODUCTION
Cores samples taken by the Cobb County Water System as part of site characterization for the Chattahoochee Tunnel present a unique opportunity to examine the crystalline bedrock of Cobb County, Georgia in an unweathered state. The cores sample tectonized schists and gneisses in the Brevard Zone and are penetrated by veins, fractures and zones of alteration associated with Brevard Zone deformation and subsequent uplift.

The goal of our project is to characterize the vein mineralogy, alteration, and vein orientations and eventually to use microthermometry of fluid inclusions within the vein filling minerals to learn about the pressure temperature conditions during alteration events. Here we report on our first observations from several intervals of core B-8.

Core B-8 is a vertical core taken near the intersection of US 47 and I-285, near the Cobb Galleria. This area had been mapped as undifferentiated Powers Ferry Formation (McConnell and Abrams .1984). Samples were taken from core B-8 at 247, 180 and 155 feet below the ground surface (bgs). Rocks recovered in the core were characterized for tunneling purposes as altered granitic gneiss composed of feldspar, quartz, biotite and minor garnet. The granitic gneiss is interlayered with biotite-hornblende-chlorite gneiss as well as chlorite schist. The granitic gneiss is interlayered with biotite-hornblende-chlorite gneiss as well as chlorite schist. Thin sections were cut from the center of bisected cores. X-ray samples were prepared by disaggregating selected portions of the rock and hand picking mineral grains or in some cases by scraping vein surfaces. Calcite was removed from powdered vein material by reacting with 10% HCl.

RESULTS
Sample from 247 feet bgs
This sample consists of tectonized gneiss with sheared plagioclase augen ranging from 1 to 20 mm in size. The core contains several white veins 1-3 mm thick. Where the veins cut plagioclase augen the plagioclase takes on a salmon pink color, Figure 1.

Figure 1. Photograph of tectonized gneiss from 247’ below the surface in core B-8. A deformed plagioclase segregation lying in the foliation can be seen in the center of the photo. A high angle laumontite, prehnite, calcite vein cuts the segregation. Alteration accompanying vein causes the plagioclase to appear pink.

The veins dip at 80 degrees to the core axis, which is assumed to be vertical, and make an angle of 60 degrees with the foliation. The zone of most intense alteration associated with the vein extends 2-3 mm into the rock. Petrographic examination of the gneiss outside of the region of alteration reveals that the gneiss consists of plagioclase, quartz, chlorite, muscovite, orthoclase, magnetite, biotite, and pale green, zoned epidote. Some of the zoned epidote grains have partially altered cores that have a light...
brown pleochroism. The pink alteration of feldspar was analyzed using x-ray diffraction. Patterns taken on hand picked, pink feldspar grains index as ordered albite. X-ray patterns from unaltered white plagioclase also index as ordered albite. In the altered zones, plagioclase is partially replaced by white mica and biotite is completely replaced by chlorite.

The veins contain blocky coarse-grained calcite, prismatic laumontite, radial sprays of prehnite and minor amounts of chlorite and epidote. X-ray diffraction was used to confirm the presence of laumontite and prehnite as the major vein filing minerals after calcite. The vein walls contain muscovite that is not aligned with the foliation. Prehnite occurs along the exterior portions of the vein, and is generally encased in laumontite or calcite, Figure 2. Calcite fills the center of the veins.

Minor amounts of bright green epidote mixed with quartz occur in cracks that in some cases cross laumontite aggregates, Figure 3.

**Sample from 155 feet bgs**

At 155 feet bgs the core consists of darker tectonized gneiss with bands that are more chlorite rich. A set of very thin (250-100 micron) white veins dip at 59 degrees and make an angle of 89 degrees with the foliation. A zone of alteration extends about 3-4 mm from the larger veins. Away from the most intense alteration, the gneiss contains plagioclase, quartz,
biotite, pale green epidote, hornblende and chlorite. Biotite grains adjacent to plagioclase are feathered and embayed, Figure 4. The pale green epidote grains are zoned and have very ragged margins. Chlorite completely replaces biotite and hornblende in the altered zone and plagioclase is partially replaced by white mica and minor amounts of calcite. The veins are filled with calcite and minor amounts of chlorite. Along the margins of the vein, muscovite is present; the muscovite does not lie in the foliation and is not present elsewhere in the rock. One of the large calcite veins was sheared with a top-down offset of 0.75 mm, Figure 5. The calcite within this vein is sheared and has an average grain size of 10 microns; muscovite adjacent to the shear zone is bent.

DISCUSSION

Although no definitive conclusions can be drawn from an examination of three small samples from a single core, the observations above do suggest several areas for continued investigation. The vein mineralogy (prehnite, laumontite, calcite, epidote and quartz) is common for shallow crustal hydrothermal vein filling. The presence of laumontite places an upper limit on temperature and pressure of about 300 C and 3 Kb (Ernst, 1976). Muscovite is associated with higher metamorphic grades than zeolite facies, so it may be possible to place a lower limit as well. Further investigation of the vein mineralogy and associated alteration, combined with microthermometry of fluid inclusions should yield a good estimate of conditions during the alteration event. Although the mineralogy of the gneisses examined here does not lend itself to determination of metamorphic grade, further investigation of the metamorphic fabric and reaction textures between biotite and plagioclase may also yield useful information. The observation that at least one of the veins contains sheared calcite hints that a systematic study of timing between alteration and deformation could yield information about the state of stress in the crust during vein formation.

REFERENCES


Figure 5: Photomicrograph of feldspar augen (F) that is cut by a sheared vein containing calcite (arrow). Muscovite (M) and in some instances calcite (C) replace feldspar in the zone of alteration near the vein.
INTRODUCTION
Geologic mapping inside the Chattahoochee Tunnel is revealing considerable information regarding the styles and likely ages of the geologic structures in the area. The purpose of this paper is to communicate some of these findings in order to stimulate thought, discussion, and research by the geologic community.

This paper is organized as a collection of topics that are only partly interrelated. These include

- the general geology of the tunnel, including the Brevard Zone
- the soil to rock transition and its role in understanding groundwater flow in the Piedmont
- the nature of the fractures
- folding

The paper is concluded with a list of questions for future research that could be done by students and faculty using the extensive quantity of cores and geologic maps that are, or will soon, become available.

PROJECT DESCRIPTION
The Chattahoochee Tunnel is a deep sewer tunnel located in Cobb County (metro Atlanta), Georgia. It is 49,625 feet long, has an excavated diameter of 18 feet and ranges in depth from about 90 to 350 feet below the ground surface. It is being excavated in two segments as a North Drive and a South Drive, and contains several shafts, intakes, underground chambers, and small connecting tunnels. The tunnel is owned by the Cobb County Water System. The geotechnical work on which this paper is based was performed by the tunnel designer, Jordan, Jones & Goulding, Inc. The tunnel is currently under construction by Gilbert/Healy, LP and is scheduled for completion in 2004.

The Chattahoochee Tunnel is designed to transmit wastewater by gravity drainage from shallow sanitary sewers to a large treatment plant, which is currently under construction. It is not intended to receive combined sewer flows nor to become over pressured relative to the surrounding groundwater. A tunnel was selected over other options in order to reduce social and environmental impacts of construction and because the bedrock in the area is considered excellent for tunneling.

JJ&G is currently engaged in geotechnical mapping of the shafts and tunnels. During 1998 to 1999, JJ&G performed extensive geotechnical investigations along the tunnel alignment, including over 13,000 ft of rock coring. The observations presented in this report are based on geological analyses of the mapping and coring.

The fieldtrip will visit the 100-foot diameter Pump Station Shaft, which is located at the southern end of the tunnel. The main tunnel between the Pump Station Shaft and the Elizabeth Lane Shaft is being excavated using drill and blast methods for distance of about 1,200 feet. About 50 feet into the main tunnel, the Interceptor Tunnel branches off to the right. The Interceptor Tunnel, which is also a drill and blast tunnel, is about 850 feet long and will divert the existing sewer along the Chattahoochee River into the main tunnel. The main tunnel heads directly into the dip, whereas the Interceptor Tunnel runs along strike.

GEOLOGIC SETTING
The Chattahoochee Tunnel is located in the Piedmont region of the Southern Appalachians. Based on the rock cores, the bedrock along the Chattahoochee Tunnel consists of medium grade metamorphic rocks with a
few small bodies of granite. The rocks consist of about 65 percent gneiss, 16 percent mica schist, 5 percent amphibolite, 5 percent granite and granitic pegmatite, 5 percent mylonitic rock, 2 percent quartzite, and 2 percent miscellaneous rock types, including mafic schist and metafelsite.

Most of the rocks along the Chattahoochee Tunnel are strongly to moderately foliated. The foliation dips fairly uniformly to the southeast at about 25 to 45 degrees. The foliation is gently undulating and contains some sharp folds. Compositional layering in the rock tends to follow the foliation in most places. The southernmost 2,500 ft of the tunnel is driven to the northwest, directly into the dip of the rock. Beyond that point, the tunnel curves to the north, such that it is driven obliquely into the dip. Considering the oblique direction of the drive and the dip of the rock, the tunnel will pass through about 20,000 feet of “stratigraphic” section.

**Brevard Zone**

The southern end of the Chattahoochee Tunnel begins in the core of the Brevard Zone. The Brevard Zone is a northeast to southwest trending belt of mylonite that extends from North Carolina to Alabama. The lateral limits of the Brevard Zone are diffuse and open to debate. Based on observations in core and in tunnel mapping, the following is suggested: the northwestern boundary consists of an inner zone and an outer zone. The inner zone is characterized by completely mylonitized rock and retrograde metamorphism below the garnet isograd. The outer zone is characterized by rare occurrences of mylonitic bands, strongly oriented foliation dipping to the southeast, and some occurrences of secondary cleavage. Aside from these characteristics, the rock in the outer zone looks little different from metamorphic rocks elsewhere in the Atlanta area. The southeastern boundary is not encountered in the Chattahoochee Tunnel.

The tunnel begins in the inner Brevard Zone. At about 2,000 feet into the tunnel, the tunnel passes into the outer Brevard Zone. The next 35,000 feet of tunnel is expected to be in the outer Brevard Zone (this location is near the intersection of Delk Road and Terrell Mill Road). Whether or not the remainder of the tunnel is in the outer Brevard Zone is questionable at the present time. Geologic mapping in the tunnel should provide a better answer.

The tunnel rocks in the inner Brevard Zone consist of interlayered phyllonite and mylonite. Phyllonite is mylonite with a phyllitic texture. Mylonite is more equigranular. Both are very fine grained to aphanitic, and medium to dark gray. The difference between the two appears to be caused by mineralogy. The mylonite consists mainly of quartz and feldspar, whereas the phyllonite contains abundant sericite. A white granitic mylonite was also observed as saprolite in the soil excavation, but it dipped away from the shaft and was not encountered in the rock excavation.

The equigranular mylonite is most abundant in and near the Pump Station Shaft. As the tunnel moves northward, the phyllonite becomes more abundant. By 1,300 ft into the tunnel the mylonite occurs only as thin, isolated layers, with the rest of the rock being phyllonite. This transition is believed to be caused mainly by a change in the bulk composition of the rock. Even in the inner Brevard Zone, compositional layering appears to generally follow foliation. At 2,000 ft into the tunnel, the phyllonite begins to become more like a very fine mica schist, and small garnets appear. This appearance of garnet marks the garnet isograd and the end of the inner Brevard Zone. At a 2,300 ft, the rock becomes a medium-grained granitic gneiss with garnet.

**SOIL TO ROCK TRANSITION**

A key characteristic of the Piedmont region is the thick mantle of residual soil that slowly grades downward into the underlying bedrock. This sequence can be divided into the soil zone, overlying the transition zone, overlying the bedrock zone. These zones are general in nature and irregular in thickness, Figure 1.

![Figure 1. Conceptual profile of the soil-to-rock transition along the Chattahoochee Tunnel.](image-url)
Weathering Index
The soil to rock transition is a function of the weathering of the rock. Rock weathering can be described on a more detailed level in terms of a “weathering index.” The weathering index is a mesoscopic term developed on this project specifically for describing rock core, but also applicable to detailed mapping of outcrops and tunnels maps (e.g., at scales of 1 inch to 10 ft).

Weathering Index terminology is shown in Table 1. Weathering Index consists of six categories, ranging from WI=0 (no weathering) to WI=5 (thoroughly weathered). Alluvial, colluvial, and fill deposits that overlie the residual soil have no weathering index because they are not weathered rock.

The Weathering Index is applicable to rock sequences that are susceptible to moderate levels of chemical weathering. This includes many igneous and metamorphic rocks, and some sedimentary rocks. It does not work well in rocks that are very resistant to chemical weathering or in rocks, such as carbonates, that tend to be completely destroyed by chemical weathering.

Soil Zone
The soil zone extends from the ground surface generally down to auger refusal. The soil zone consists primarily of highly and thoroughly weathered rock (WI≥4), plus any overlying deposits. The soil zone is typically 20 to 60 ft thick, but may be thinner or thicker in some places.

The soil zone consists of three layers itself. The uppermost layer consists of surficial soils, including topsoil, colluvial soil, and alluvial soil. The middle layer is consists of classic saprolite (WI=5), and generally comprises the majority of the soil zone. The lowermost layer is commonly referred to by foundation engineers as “partially weathered rock” (PWR), and consists mainly of highly weathered rock (WI=4). Auger refusal generally occurs at the base of the soil zone.

The soil zone commonly contains layers and lenses of less weathered rock (W≤3). These lenses and layers can cause shallow auger refusal. The base of the soil zone is marked by the point at which the majority of the rock permanently becomes WI≤3. Likewise, layers of WI=4

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### TABLE 1

<table>
<thead>
<tr>
<th>Weathering Index</th>
<th>Name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Fresh</td>
<td>No visible discoloration, even along joints. Joints generally healed or lined with euhedral crystals.</td>
</tr>
<tr>
<td>1</td>
<td>Faintly Weathered</td>
<td>No visible discoloration of rock matrix. Visible discoloration limited to surface of major, open fractures.</td>
</tr>
<tr>
<td>2</td>
<td>Slightly Weathered</td>
<td>Visible discoloration extends into rock matrix for a short distance but does not fully permeate the rock. Rock appears to be full strength except along fractures.</td>
</tr>
<tr>
<td>3</td>
<td>Moderately Weathered</td>
<td>Visible discoloration extends through rock matrix. Feldspar and mafic minerals partially but not fully degraded. Matrix strength of rock appears somewhat reduced, but the rock generally is not breakable by finger pressure alone. Can generally be recovered using standard rock coring techniques but with low RQD values. Generally causes auger refusal.</td>
</tr>
<tr>
<td>4</td>
<td>Highly Weathered</td>
<td>Matrix strength of rock is greatly reduced, and rock should be breakable with strong finger pressure. Weathering permeates entire rock. Generally cannot be recovered using rock coring techniques. Identified in soil borings where SPT N-value exceeds 100 blows per ft. Commonly described as PWR (“partially weathered rock”) by foundation engineers.</td>
</tr>
<tr>
<td>5</td>
<td>Thoroughly Weathered</td>
<td>Rock completely degraded into soil but with the original texture and structure of the rock clearly visible. (In the Atlanta area, this is known as saprolite.) Cannot be recovered using standard rock coring techniques. SPT N-value less than 100 blows per ft.</td>
</tr>
</tbody>
</table>
(PWR) rock may occur within larger bodies of (W=5) rock, and vice versa.

The soil zone is characterized by intergranular porosity developed between the mineral grains. This intergranular porosity weakens the material and provides considerable storage for groundwater. Because the grains interlock, however, the permeability of soil zone tends to be low.

**Transition Zone**

The transition zone lies below the soil zone and consists of fractured rock that is degraded by weathering, at least along fractures. The transition zone generally consists of moderately (Wl=3) to slightly (Wl=2) weathered rock. Layers and lenses of all weathering indices may be present in the transition zone, however. The transition zone ranges from less than 5 ft thick in some places to more than 50 ft thick in others.

The transition zone is characterized by open, weathered fractures. Weathered grain boundaries are present along the fractures, making the fractures structurally weak. Penetrative weathering into the rock matrix weakens the intact rock, especially in moderately weathered rock (Wl=3), but generally provides little intergranular porosity. The transition zone is characterized by higher permeability, commonly greater than 10^{-4} cm/s.

**Bedrock Zone**

The Bedrock Zone consists mainly of fresh to faintly weathered rock (Wl≤1). Fractures in the bedrock zone are typically cemented, tight, or stained. Penetrative weathering into the rock matrix weakens the intact rock, especially in moderately weathered rock (Wl=3), but generally provides little intergranular porosity. The transition zone is characterized by higher permeability, commonly greater than 10^{-4} cm/s.

**Groundwater Implications**

The soil zone, transition zone, and bedrock have differing water bearing properties along the Chattahoochee Tunnel. These properties are related in part to the nature of rock fractures in the Brevard Zone. It is not known whether the observations described below are applicable to other areas in the Piedmont.

The water table is typically high in the soil zone. The soil zone is the principal groundwater storage reservoir but has low permeability. Crawford (personal communication) has compared the soil zone to a leaky confining layer. In hydrogeology, a leaky confining layer is a layer overlying an aquifer which has relatively low permeability but which leaks enough water over a broad area to recharge the underlying aquifer. Gradients in the soil zone have strong vertical components. Water flows downward in the upland areas and upward along the streams.

The transition zone is the principal transmissive layer. The numerous open fractures allow water to flow from recharge area in the uplands to discharge areas in the streams. The transmissivity of the flow system at any give point depends on the thickness of the transition zone. Based on packer tests, the transmissivity of the transition zone is commonly in the range of 20 to 60 ft^2/day where it is well developed. Where it is very thick and well developed, the transmissivity may reach 100 ft^2/day. Wells completed in the transition zone generally require a screen and filter pack to prevent siltation. The yield from transition zone wells is limited by the inability to draw the well down as deeply as might be desired.

The bedrock zone is transmissive only through scattered, open fractures. These fractures generally have negligible storage but may be very permeable. Based on packer tests for the Chattahoochee Tunnel, the transmissivity for the bedrock zone is generally less than 2 ft^2/day, but ranges up to 25 ft^2/day where large fractures are present. One location had a bedrock zone transmissivity of 50 ft^2/day in a highly fractured zone. Wells drilled in the bedrock zone appear to function because they connect to the transition zone through large, open fractures. If a well can intercept several good fractures oriented in different directions, then a much broader area of transition zone can be tapped, and the yield of the well will be large. Bedrock zone wells also are deep enough to allow large drawdowns, thereby increasing the radius of influence and yield. Good bedrock zone fractures are not present in most places, however. This results in a high percentage of attempted wells being abandoned for lack of adequate yield.

Natural groundwater flow occurs mainly in the transition zone, as evidenced by the pronounced weathering present on the fractures. This weathering indicates that fresh oxidizing, water in chemical disequilibrium with the unweathered rock is actively moving through the system. In contrast, many water-bearing fractures in the bedrock zone lack any evidence of weathering or staining. This lack of weathering indicates that the water is in chemical equilibrium with the bedrock. Chemical equilibrium occurs when groundwater moves very slowly or is stagnant. When bedrock wells tap these bedrock fractures, it is likely that they are creating a new flow system through
previously stagnant water, rather than intercepting an existing flow system.

**FRACTURES**

The metamorphic rocks along the Chattahoochee Tunnel contain abundant fractures. These fractures are not so closely spaced as to classify the rock as shattered, but neither are they so rare as consider the rock massive.

Fractures have been measured at the Pump Station and in associated drill and blast tunnels. A stereonet of these measurements is shown in Figure 2. This stereonet shows four major fracture sets, labeled F1 through F4, plus numerous random fractures.

![Stereonet showing fracture sets](image)

**Foliation Fractures**

Foliation fractures form along schistose laminations in the rock. They tend to be more closely spaced in the more schistose rocks, and to be more widely spaced in the more equigranular rocks. They vary from smooth to rough, and tend to be broadly undulating. In the transition zone, foliation fractures tend to be very common, open, and weathered. In the bedrock zone, they are more typically tight. These tight fractures form preferential breakage planes during blasting, and can be readily observed in the Pump Station Shaft. Some open, weathered foliation fractures do occur in the bedrock zone, however. Foliation fractures occur principally in fracture set J1. Due to undulations in foliation however, foliation fractures may also occur at random orientations, with dips ranging from horizontal to more than 60 degrees, and with strikes ranging from N-S, clockwise around to E-W. Foliation fractures longer than 60 ft have been observed with regularity in the Chattahoochee Tunnel.

Foliation shears are a special type of foliation fracture. Foliation shears are large (typically much greater that 100 ft wide) shear planes in the rock that dip to the southeast, in the approximate plane of foliation. In the bedrock zone, foliation shears typically contain gouge and white clay. In the transition zone, they typically severely weathered. Weathered foliation shears appear to be good conduits for groundwater, and to cause the transition zone to be locally thicker, Figure 3.

**High-Angle Fractures**

High-angle fractures are characterized by a steep dip (generally greater than 70 degrees) and an orientation that is unrelated to the type or foliation of the rock. High-angle fractures are typically smooth and either...
planar or broadly undulating. In fresh rock (WI=0), high-angle fractures are commonly cemented with calcite, pyrite, zeolite, or other fillings. These cements tend to be considerably weaker than the surrounding rock and form planes of preferential breakage. Where the rock is weathered (WI ≥ 1), these fillings may be dissolved away or altered to clay, resulting in loose, open fractures with clay coatings. High-angle fractures range in lengths from greater than 60 ft to less than a foot.

High-angle fractures in the Chattahoochee Tunnel follow what appears to be a sinusoidal distribution with regard to length and spacing. At the top of the sine curve, fractures are very closely spaced and long. Moving away from the top of the curve, spacings become broader and fractures become shorter. The fillings also become less prominent. At the bottom of the curve, there are few high-angle fractures, and those that are present tend to be very short, Figure 4.

Close Conjugates. Many high-angle fractures occur as “close conjugates.” Close conjugates are conjugate high-angle fractures that have a smaller than normal dihedral angle between them. Under low confining stress, the conjugate shears typically form at an angle of 60 degrees to one another. As confining pressure increases, however, this angle becomes smaller. At the highest confining pressures, such as during mylonite formation, the shears become parallel to one another. Close conjugates are conjugate shears that are intermediate between these two extremes.

Close conjugates can be observed in outcrop, and appear as undulations in a fracture surface. The undulations consist of long, planar segments, followed by tight bends. The angles of the bends are typically on the order of 20 degrees.

Fracture Fillings. A variety of fillings have been observed in the high-angle fractures. The most common are epidote, zeolite, calcite, pyrite, and gypsum. Epidote is observed in very large high-angle fractures, and is commonly associated with altered feldspars. Zeolite is much more common than epidote and is observed in large fractures. When exposed to water, the zeolite appears to alter to white clay. Calcite and gypsum are commonly observed in medium-sized fractures. The finest fractures tend to have no fillings, but to be tight.

These fracture fillings represent a range of temperatures, from epidote at the high-temperature end, to gypsum at the low temperature end. The presence of epidote and zeolite in high-angle fractures indicates that these fractures were forming during the waning of Appalachian metamorphism.

Strike Fractures

Strike fractures are oriented orthogonally to foliation. They strike parallel to foliation but dip in the opposite direction. Strike fractures occur principally in fracture set J4. Strike fractures tend to be rough, open, and weathered. Strike fractures are more common in the transition zone and become less common with depth.

Timing of Fracture Formation

Two generations of fracturing have been recognized in the tunnel mapping. The first generation appears to be associated with the building of the Appalachian mountains, probably in the latter stages of the Alleghenian Orogeny. The second generation appears to be associated with isostatic uplift and lithostatic unloading, and are probably of Cenozoic age.
The first generation consists primarily of high-angle fractures and foliation shears. The high-angle fractures are filled with a variety of fillings, as described previously. These fillings suggest gradual cooling as the style of deformation changed from ductile to brittle. The orientations of the high-angle fractures and foliation shears suggest a northwest to southeast compressional regime, consistent with the general trend of Alleghanian structures in the region. Because these fractures tend to be filled, they tend not to yield much groundwater, unless reactivated, as described below.

The second generation consists of foliation fractures, strike fractures, and reactivated high-angle fractures. Instead of precipitated mineral cements, fractures of the second generation tend to be weathered and open, which makes them excellent conduits for groundwater flow. Second generation fractures are most prevalent in the Transition Zone. They become rare in the bedrock zone, Figure 5.

Most first generation fractures show shear offset where good marker layers are present. This offset is commonly on the order of a few centimeters in smaller fractures. In some cases, however, large fractures have shown offset greater than the size of the tunnel. These small faults include both high-angle fractures and foliation shears.

Most second generation fractures appear to be extensional in nature. They are believed to form in response to a reduced least principal stress, which is upward. Because the foliation direction is the weakest direction of the rock, however, an extensional fracture forms parallel to the dipping foliation, rather than horizontally. This extensional fracture along foliation is essentially an exfoliation fracture.

Extension along dipping foliation creates a geometry problem. This is exacerbated because extension appears to increase as depth becomes shallower. This increase in extension is manifest by an increase in the number of fractures, a decrease in the fracture spacing, and an increase in the apertures. Stepping back, these fractures can appear a the pages of a book that got wet: fanning upward on the updip side. To compensate, the strike fracture forms as an orthogonal to foliation. The strike fracture allows vertical movement, as shown below. Reactivated high-angle fractures also allow for vertical movement. Upon reactivation, the zeolite, calcite, and gypsum cements tend to weather away, leaving an open, weathered fracture. It is uncertain as to whether the strike fractures are reactivated first-generation fractures, or whether they are completely new fractures. They do appear to be much more common in the transition zone than in the bedrock zone.

FOLDS AND FOLIATION

Tight similar folds and shallow conical folds are commonly observed in tunnel mapping. Large similar folds have been mapped in the field for many years along the tunnel alignment. Detailed measurements along large, undulating foliation planes may provide insight into the nature of folding in the area.

Strike and dip measurements were made along prominent foliation surfaces at the Pump Station Shaft. These planes were mineralized with a several millimeter-thick layer of magnesium oxide. These foliation surfaces were observed to be continuous over many tens of feet.

Figure 6 shows a stereoplot of the various orientations along one of these surfaces. The surface undulated and contained some prominent, sharp bends. Measurements were numbered in order along the surface, and these numbers are plotted next to the poles on the stereoplot. The measured surfaces fall on small circles, which represent shallow, conical folds. Conical folds are analogous to a wobbling top, where the spindle tracks larger and larger circles around a central, imaginary axis. The axes of the conical folds fall on a single great circle, indicating a cylindrical fold. The pole to this great circle is labeled A on Figure 6.

Two other prominent foliation surfaces were similarly analyzed. These surfaces also had conical fold axes that formed great circles. The poles of these other great circles are labeled B and C on Figure 6. Together, the three cylindrical fold axes A, B, and C lie in a single plane, oriented N47°E, 46°SE. This single plane may be the axial plane of the whole sequence of similar folds.
that are observed in the area, including the prominent Vinings antiform.

![Stereoplot of prominent foliation shear surface](image)

**Figure 6.** Stereoplot of prominent foliation shear surface. Points numbered consecutively along outcrop. Points 1-5 located about 70 ft away from others, along strike. Small circles are cones representing shallow conical folds, which cause most of undulations. Conical fold axes (stars) fall on great circle, indicating a larger cylindrical fold. Points A and B are cylindrical fold axes for two other prominent foliation shear surfaces in the area. All three cylindrical axes fall on a master great circle (dashed) oriented N47°E, 46°SE.

**RESEARCH QUESTIONS**

**Thesis Topic:** If the dihedral angle is related to confining pressure, what constraints does the dihedral angle of the close conjugates place on the timing, depth of burial, and metamorphic history of the rocks during fracture formation? How is this affected by rock lithology?

**Thesis Topic:** What temperature and pressure constraints do the fracture fillings place on the environment in which these fractures form? Which fractures formed earlier? Which fractures formed later?
Petrography of Rocks from the Chattahoochee Tunnel, Inner Brevard Zone, Cobb County Georgia

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Introduction

The Brevard Zone (Brevard Zone) is a linear topographic and structural feature that runs parallel to the main trend of the southern Appalachians from Horseshoe Bend, Alabama to Mount Airy, North Carolina (Bobyarchick 1999, Higgins 1966). The Brevard Zone has been the object of debate since first recognized by Arthur Keith in 1905 (Bobyarchick 1999, Medlin and Crawford 1973). Most of the information concerning the Brevard Zone was collected between the mid-1960’s and late 1970’s and based on various surface outcrops and saprolite exposures. Previous structural analyses suggest early ductile deformational histories including dextral strike-slip faulting with displacements ranging from 25-135 km (Reed & Bryant 1964; Higgins 1966; Vauchez 1987). Later brittle dip-slip movement has been suggested based on the occurrence of a subset of lineations that rotate from regional strike into the line of strike of the Brevard Zone (Higgins 1966; Evans and Mosher 1986). A tunneling project, the Chattahoochee Tunnel Project (CTP), in Cobb County, Ga., presents a new opportunity to obtain fresh samples and to investigate the subsurface geology of the Brevard Zone. The CTP is a sewer tunnel that begins within the Brevard Zone in Vinings near Fulton County and terminates 15.3 km north at Indian Hills Golf Course beyond the Brevard Zone, Figure 1. Trend of the tunnel is approximately perpendicular to the Brevard Zone. This tunnel project has allowed the first author an opportunity to map the geology of the tunnel and Brevard Zone, and collect fresh samples and analyze the structure of the Brevard Zone in 3 dimensions. Here, we report on the initial petrographic observations within the incomplete tunnel as well as on samples from drill cores from the vicinity of the tunnel.

For the purpose of this paper, the Brevard Zone in north central Georgia is divided into an inner and outer zone, and the contact between the two is set at the Long Island Creek fault, located just to the north of the R.L. Sutton Wastewater Reclamation Facility. The purpose for this division lies in contrasting degrees of mylonitization of rocks on opposite sides of the Long Island Creek fault recognized by one of us (J. Raymer and R. Kath (personal communication, 2000)). The rocks of the inner Brevard Zone south of
the Long Island Creek fault have a more mylonitic-phyllic texture than the Long Island Creek gneiss north of the fault.

The Long Island Creek gneiss is a medium grained, granitic gneiss that exhibits some effects of mylonitization including recrystallized quartz and muscovite fishes. Plagioclase feldspar twins are also bent. These rocks do not, however, contain the more extreme deformation structures such as secondary foliations, obliterated twin planes, and tightly folded gneissic bands found in rocks of the inner zone of the Brevard Zone. The rocks that constitute the inner Brevard Zone are predominantly S-C mylonites and striped gneisses.

PETROGRAPHY

The striped gneisses are the dominant lithology at the southern end of the drill and blast tunnel that terminates at the pump station. Outcrops of the striped gneiss are difficult to break, and break into very angular fragments, due to the high quartz content. A typical mode is 50% quartz, 20% biotite, 10% muscovite, 7% plagioclase feldspar, and minor garnet, chlorite, and opaques. Quartz occurs within the matrix and as veins, some of which are tightly folded. Matrix quartz exhibits undulose extinction and is aligned in the foliation direction. Plagioclase feldspar occurs as anhedral, gray porphyroclasts, and ranges in diameter from 0.2 mm to 2.5 mm. Most twin planes have been obliterated while some still remain. Garnet occurs as porphyroblasts within the drill and blast tunnel and was not observed in thin sections of drill core samples. Muscovite only occurs as small, sparse fishes apparent in thin section. Biotite occurs in local concentrations as grains up to 0.3 mm in length and helps define foliation with muscovite. Chlorite occurs within fractures and is not widespread. Quartz with plagioclase feldspar define felsic layers, typically 3 cm thick, while biotite defines mafic layers up to 5 cm thick.

S-C mylonites become more common as one progresses north along the drill and blast tunnel. A typical mode is 35% muscovite, 25% biotite, 20% quartz, 7% plagioclase feldspar, 7% amphibole, 2% garnet, and trace opaques. Muscovite grains are large (up to 5 mm) and have been bent and kinked. Biotite grain size is also larger relative to its occurrence within the striped gneiss. Grains are up to 0.7 mm in length and have been bent and kinked. Muscovite and biotite orientations define observed primary and secondary foliations. Quartz occurs within the matrix of the rock as well as in veins. Plagioclase feldspar occurs as porphyroclasts within the foliation and are anhedral, and gray in color. Garnet occurs as porphyroblasts and are subhedral and up to 5 mm in diameter. Sinuous inclusion trails suggest grain rotation. Amphiboles are commonly euhedral, zoned, and 1-2 mm in diameter. In thin section, epidote occurs as small (0.2 mm) grains that overprint both foliations. Anhedral staurolite grains up to a mm in diameter were observed in one sample of drill core. Commonly in the tunnel outcrops, the two lithologies are repeatedly interlayered (Figure 2). However, it is not uncommon to walk through hundreds of feet dominated by one unit containing seams (between cm to m thick) of the second lithology. Following is a brief log of the distribution of rock types in the tunnel walls from south to north. For the first 67 m along the drill and blast tunnel, striped gneiss is the dominant lithology. For the following 27 m, S-C mylonite is the dominant lithology. For the next 61 m, striped gneiss again becomes the dominant lithology. For the remaining (at time of writing) 78 m of the drill and blast tunnel, S-C mylonite becomes the dominant lithology. From the Elizabeth Lane access shaft located 369 m north of the pump station to the beginning of the current work area 488 m of the pump station, S-C mylonite is the dominant lithology and remains so until the contact with the Long Island Creek gneiss at 716 m. At time of writing, the last 62 m of the drill and blast tunnel have not yet been excavated.

Deformation

The rocks of the Brevard Zone have undergone at least two different ductile deformation events and possibly two brittle events during its active history.
The first ductile event affecting the rocks of the Brevard Zone produced the $S_1$ foliation defined by biotite and muscovite orientations in the S-C mylonite. This primary deformation event also probably resulted in the formation of banding within the gneiss. The second ductile event resulted in the development of the $S_2$ foliation defined by orientations of bent muscovite and biotite in the s-c mylonite and possibly some recrystallization of the gneiss. An important observation is that the $S_2$ foliation within the mylonite does not penetrate into the striped gneiss. The second event may have also produced the observed tight folds within the felsic bands within the striped gneiss, Figure 3. The quartz grains in the striped gneiss have undergone grain boundary migration recrystallization and dynamic recrystallization in response to strain. Under simple shear conditions and correct temperatures, quartz will deform plastically before other minerals will. This recrystallization may be related to the $S_2$ foliation in the S-C mylonites and requires temperatures in excess of approximately 400°C and an applied stress (Passchier and Trouw 1998). High temperature alone will not produce these structures.

Pseudotachylites up to 1.5 mm thick (Figure 4) crosscut the foliation of the striped gneisses and formed within the Brevard Zone due to brittle events. The pseudotachylites commonly contain a black, very fine-grained matrix with fragments (0.3mm in diameter) of quartz and plagioclase feldspar, chlorite is disseminated throughout. Under uncrossed polars, pseudotachylites are olive green to dark olive in color and slightly pleochroic due to chlorite. In one sample, two pseudotachylites cross cut each other at almost 90° suggesting two distinct brittle episodes of deformation, Figure 4.

**METAMORPHISM**

The rocks of the Brevard Zone have undergone amphibolite grade, Barrovian style metamorphism suggested by the common coexistence of garnet and biotite and rarer assemblages involving staurolite or strongly colored amphibole. Zoned amphiboles in some rocks contain dark cores (Figure 5), which may reflect an earlier igneous or metamorphic event. Amphibole rims are probably part of the peak metamorphic assemblage, but microprobe analysis has yet to be performed to verify this hypothesis nor...
to characterize garnet and plagioclase compositions. Retrograde metamorphism is suggested by the orientation of epidote grains, which grew across $S_1$ and $S_2$ foliations.

**BULK COMPOSITIONS**

Distinct bulk compositions may be responsible for the differing characteristics of the two lithologies of the CTP. Alternatively the S-C mylonites may indicate high strain rates in localized shear zones. However, relatively high muscovite and biotite concentrations of the strongly foliated S-C mylonite suggest a bulk compositional difference between the two lithologies. The mica-rich mineralogy of the S-C mylonite suggests an aluminous, and probably sedimentary protolith. The striped gneiss, which contains significantly lower amounts of the micas, recrystallized rather than accommodating the applied stress during a simple shear event. Also, features formed by brittle deformation are commonly restricted to the striped gneiss, (Figure 6), whereas the S-C mylonite accommodates the stress within the muscovite and biotite minerals through bending and kinking. The distinct behavior of the striped gneiss reflects its relatively aluminum-poor composition; we infer its protolith was a quartz rich sedimentary rock or a felsic volcanic.

**REFERENCES**


INTRODUCTION
The Brunton® compass is used by more geologists for field mapping of geological objects than other brands. This preference, especially in North America, is because Brunton provides a precise sighting-clinometer and hand level capability, and can be used at both waist and eye levels; advantages that are absent in other brands such as Silva which lacks a leveling system for sighting bearings (Compton, 1985). Detailed measurement of geological objects, such as fold hingeline, axial trace, and axial plane, and geological mapping becomes essentially impractical without the use of the compass (i.e., Brunton).

In this paper, we will review the application of the Brunton compass in the measurement of a variety of planar and linear geological features (e.g., structural, sedimentary, stratigraphic), and discuss the use of the compass in mapping and measurement of stratigraphic sections, vertical angles, height, etc. Some discussions are given in the context of the lower hemisphere stereographic projection of the geological objects for the sake of clarity and practical value.

THE BRUNTON COMPASS
Brunton compasses have three main parts, box, sighting arm, and lid. The box contains most of the components: the needle; bull’s eye level (round level to read horizontal angles); clinometer level (barrel-shaped) and clinometer scale (for reading vertical angles); damping mechanism (to more efficiently stabilizing the needle); lift pin (to lock the needle); side brass screw and index pin (to set and display the declination); graduated circle or card (to read the bearing). The needle has two ends: the north-seeking end (commonly white in genuine Brunton compasses, labeled ‘N’ in others), and the black, south-seeking end. The north-seeking end of the needle is pulled down in the northern hemisphere where the magnetic inclination is downward. An additional small weight attached to the south-seeking end of the needle provides proper balancing of the needle. The weight needs to be reversed if using the compass in the southern hemisphere where the magnetic inclination is upward.

The lid, attached to the box with a hinge, contains the mirror with the axial line and oval sighting window (for waist- and eye-level sighting), and the sight. The long sighting arm, attached to the box with a hinge, has a long, oval rectangular cutout or slot (for reading linear objects), and a tiltable sighting tip, which is used for aligning the line of sight. The circle card of the Brunton compass is designed in two traditional scales. The azimuth scale uses three digits, with north at 000° or 360°, and south at 180°. The quadrant scale uses an alphanumeric notation (e.g., N60°E, S20°W) with the card graduated in four 90° quadrants (NE, SE, SW, NW); north and south lie at the two upper and lower 0° marks, respectively.

The direction of a line on the ground is given by the bearing of the line, which is the horizontal angle between the line and a reference, commonly north in the quadrant scale, or 000° (marked as 0° on the card) in the azimuth scale. The reference, however, can
also be the south (S) in the quadrant scale, when reading the bearing (i.e., trend) of south-trending linear objects. The position of ‘E’ and ‘W’ are reversed on the circular card; ‘E’ lies left of the 0° mark (i.e., at 9 o’clock), and ‘W’ is to the right of the 0° (i.e., 3 o’clock) mark on the card. The reversal is designed to make the correct reading of the bearing possible. To appreciate this fact, notice that the north-seeking end of the needle always stays pointing north even when the compass dial is rotated. For example, to read a bearing of 045°, we level the dial and then turn right of north, but the north-seeking end of the needle turns to the left of 0°, which is actually east on the dial; so we read a correct bearing.

The Earth has geographic or true N and S poles, where the rotation axis intersects the Earth’s surface, and magnetic poles, where the magnetic lines of force emerge (magnetic S) or converge into the Earth (magnetic N). As a magnetic device, the needle of the Brunton compass (a magnet), when freely suspended, seeks the magnetic poles, which generally are not the same as the true north, except in some areas on Earth. A compass needle is a magnet, and the north pole of any magnet is defined as the side which points to the magnetic north when the magnet is freely suspended. The correct name for this end of the needle is "north seeking pole". Maps label the magnetic pole in the northern hemisphere as the "North Magnetic Pole".

The angle between the true north and the magnetic north is called magnetic declination. Declination varies with location, time (secular, diurnal), local magnetic anomalies, altitude (negligible), and solar magnetic activity (Goulet, 1999). Declination is therefore the angle between where a compass needle points and the true North Pole. Magnetic declination is constant along the so-called isogonic lines. The 0° declination (agonic) line passes west of Hudson's Bay, Lake Superior, Lake Michigan, and Florida. The N magnetic pole was positioned in 1999 at 79.8° N, and 107.0° W, 75 in the Canadian Arctic, 1140 km from the true N. The vertical angle between the magnetic vectors relative to the level (horizontal) ground is the magnetic inclination, which varies with latitude; it is 90° at the north magnetic pole, and 0° at the magnetic equator.

Determining the magnetic declination
If the compass needle points east or west of the true north, the offset is called east or west declination, respectively. The standard is to use the magnetic north (MN) as a reference for declination, even in the southern hemisphere. To determine the magnetic declination in a study area we can use: (1) Published topographic maps; some maps display an out-of-date declination indicated by the angle between two arrows pointing to the magnetic north (MN) and true north (GN). (2) Published or online isogonic charts, which are available at:

http://geomag.usgs.gov/chartsdo.html
http://geomag.usgs.gov/models.html

(3) Online calculator to determine the latest magnetic declination for a given location (latitude and longitude) and year

http://www.geolab.nrcan.gc.ca/geomag/e_cgrf.html
or http://www.resurgentsoftware.com/geomag.html

Setting the declination
Geologists use the compass for mapping and measuring linear and planar objects. The magnetic declination is set by turning the brass screw on the side of the compass box. For a west declination of say 16° (i.e., declination is 16° west of true north), turn the card west, i.e., counterclockwise (by turning the screw) so that the index pin points to 16° on the side of the card marked with ‘W’ in the quad scale, or 344° in azimuth scale. For an east declination of 16°, turn the card east (i.e., clockwise), so that the index pin points to 16° on the side of the card marked with ‘E’ in the quad scale, or 016° in azimuth scale.

The concept of domain
One of the objectives of studying a complexly deformed area (e.g., refolded folds) is to identify domains (subareas) within which the fabric data of, for example, folds, lineations, foliations are homogeneous. This means, for example, that the hingelines and/or fold axes, and the poles to the axial planes (or axial planar foliation, if it exists) of all minor folds define maxima (i.e., cluster distribution), with the mean axis lying on the mean axial plane. The boundaries of the domains are identified (mapped) by locating the adjacent stations at which specific fabric data are homogeneous. The homogeneity in each domain reflects two major facts: (1) Homogeneity of the strain which results in equal extension in a strain field in which the axes of the maximum principal extension are parallel at every point, keeping originally-parallel lines and planes parallel, and straight lines straight. (2) Homogeneity of the rock, i.e., rock properties is the same at each point in the rock continuum during the deformation. Geologists cannot produce a useful map of, or obtain useful information from, moderately- to highly-deformed areas, without knowing how to use the compass to collect the fabric data and to delineate the domain boundaries. Thus, we need to know how to measure linear and planar objects of all kinds, such as sedimentological and structural fabric elements, and map lithostatigraphic boundaries such as contacts.
**Attitude of linear and planar geological objects**

Although most geologic structures are generally either curvilinear or curvilinear, they can be approximated as either linear or planar at specific scales or domains. For example, a primary linear structure such as the crest of ripple marks or flute casts on a bed may be folded around the axis of a fold. At the scale of a large fold, these linear objects are curved, i.e., have a systematically distributed orientation (e.g., small circle or great circle distribution). However, within each limb of the fold (a domain), the orientation of these structures may be homogeneous, that is, the flute casts or ripple crest are subparallel to parallel. On each limb, the fabric data of minor folds may have a homogeneous distribution.

The attitude of both linear and planar objects has two general components: bearing and inclination. **Bearing** is the horizontal angle between a line and a specified reference (N or S). The “line” either is the horizontal projection of an inclined linear object, or a horizontal line on an inclined plane. Bearing is a scalar feature, i.e., it just is a number (e.g., 045° or N45°E). **Inclination**, on the other hand, is the vertical angle between a linear or planar object and the horizontal. The convention for direction of inclination is down, i.e., we measure the angle from the horizontal down (not up), especially when we process the data on the lower hemisphere, equal area projection (mineralogists also use the upper hemisphere for crystals). Inclination is a vector, meaning that it has two components: an amount (angle below the horizontal), and an orientation specifying the direction to which the planar feature is inclined down (e.g., 30°NW).

Attitude is too general, and its two components: bearing and inclination, take different meanings when dealing with linear and planar element. For planar features such as bedding (the boundaries of a bed), fault, and foliation, the bearing and inclination become strike and dip. Note that strike is a scalar, and dip is a vector. **Strike** is the bearing of a horizontal line on an inclined plane. Since strike is the bearing of a horizontal line, we can read the bearing of either of its ends; thus, 000° and 180° are the same strike. **Dip** is the inclination of an inclined plane. For linear fabric such as hingeline, axis, or lineation, we use trend and plunge to represent the bearing and inclination. Notice that horizontal planes don’t have any strike because they don’t intersect the horizontal along a line.

**Trend** is the bearing of a linear object measured in the direction to which the line is inclined down. **Plunge** is the amount of the inclination of the linear feature. Thus, both trend and plunge are scalars; together they define the line vector. For example, a 060°, 30° (also written as 30°, 060°, or 30°, N60°E) is a pair of trend/plunge (direction/magnitude) or plunge/trend, which means that a line plunges 30° down below the horizontal in the 060° direction. Linear objects can also be defined by their pitch on a specific plane. Notice that vertical lines don’t have any definable trend, and that the trend of a non-horizontal linear object must be read from a reference (e.g., N) to the direction that the line plunges. Thus, a trend of 000° and 180° are not the same thing (contrast this with strike!). In practice, it is extremely difficult, if not highly error-prone, to measure the trend of steeply plunging linear object; in such cases we use pitch. Notice that the trend of any line on a vertical plane is the same as the strike of that plane (a useful geometric fact). **Pitch** is the acute angle measured on a plane, from the strike of the plane that contains the line, toward the line (the sense is important!). For example, a pitch of 40°SW (read as: 40° from SW) means that the line is pitching 40° from (not to!) the SW end of the strike line of a plane that contains the line. Notice that pitch generally is not a horizontal or vertical angle, except for horizontal and vertical planes containing linear features. Pitch is an alternative to trend and plunge, although, sometimes, it is the only practical way of measuring a line correctly, especially if the line is steeply plunging.

**Measuring the attitude of linear objects**

Measuring trend and plunge: If the linear object is below our line of sight, open the sighting arm and the lid, and align the open, long slot of the arm parallel to the linear feature. If the linear feature is above our head (e.g., on a bedding above us), stand under the object and align the linear feature with the black axial line on the mirror on the lid of the compass. In either case, level the bull’s eye, round level while aligning. If the linear object is plunging, only one of the needles (the north-seeking or the south-seeking) indicates the true trend of the linear feature. This is a case where many inexperienced geologists can make a common, critical mistake! Some people have the habit of only reading the north-seeking (white) needle of the compass, or vice versa, which is an error-prone practice. When using the Brunton compass we should be color-blind, and only read the direction of the needle that is correctly indicating the direction to which the line is plunging (down, not up!). Thus, the trend of only one of the needles is correct when reading a line. To figure out which one, we should...
be aware of the local geographic directions, that is, know the direction of north or south in the field at all times. For example, if we are measuring a linear object plunging down to the south (S or somewhere in the SE or SW quadrants), we must read the trend indicating any one of these southern directions (e.g., 120° or 560° E), and not the diametrically opposite northern directions (i.e., 300° or N60°W) indicated by the opposite end of the needle. For a plunging line, 120° and 300° are not equivalent; only one is the true down direction (120° or 560° E in this case). The true direction of the trend may be indicated by the white or the black needle; the color depends on how we hold the compass (sighting arm away or toward our body), and on which way we are facing in the field (looking north or south). Therefore to avoid a common mistake, no matter how you are holding the compass or which way you are facing; just know where the geographic N or S is in the field, and ask yourself this question: Which way is the line going down (i.e., plunging)? If it is plunging to around the N, then read the needle (white or black) that points to N or in the NE or NW quadrants and not the opposite directions. This is the easiest and most practical way of correctly measuring a line. Of course, if a linear feature is non-plunging (a special case), we have the freedom of reading either the white or the black needle, because the line is horizontal (both ends are the same).

Example: We are measuring the crest of a ripple mark which is roughly trending somewhere around north (we know which way is N in the field because we have the compass!). The crest of the ripple mark is plunging, and lies on a bedding, which is dipping. Align the compass’s sighting arm with the crest and then read either the direction indicated by the white or the black needle that points somewhere to the north. Thus, if the black needle points to N20°W and the black needle points to the S20°E, we must read the black needle. Don’t wrongly assume that the white needle gives you the north readings; a common misconception.

Measuring vertical angles, height, and distance
To measure vertical angles, fold the lid and use the compass as was described for measuring the plunge of lines, i.e., with the clinometer. The vertical angle (θ) can then be used to calculate the height (h) of an object (e.g., wall, tower, mountain peak) using the equation h = x tanθ, if we know the distance (x) to the object. We can also use the trigonometric functions to calculate the horizontal distance (x) from point A to an object located at point B as follows. Walk from point A to another point C such that AC is perpendicular to line AB. This is done by taking a bearing at 90° to the bearing of AB with the compass. Use a tape or a measured pace (if pace spacing is known). In practice, we define AC to be 10 meters; or walk from A to C by 10 meters with our pace. Read a bearing from point C to point B. Subtracting the two bearings gives the angle β between AB and CB. Now we have a right angle triangle ABC with AC = 10 m, AB = x, and a known angle β. Use the equation tanβ = AC/AB = 10m/x, and calculate x in meters.

If the linear object of interest is steeply plunging, it is better to use pitch instead of the trend and plunge. Measuring pitch is only possible if the linear feature lies on a physical plane. For example, if a set of slickenlines (striations) plunges (e.g., around S) on a fault, we measure the striations as follows. First, measure the plane (i.e., fault) that contains the linear features (see next section for this). Next, measure the pitch of the striations on the fault plane as follows. The Brunton compass has a circular, high relief ring on its back, which is designed for measuring pitch. Open the compass (the arm and lid opened completely) and align the edge of the lid and box with the line while the whole ring on the back of the compass touches the fault. If the clinometer, barrel-shaped level is not centered in this position, gently move the box off the plane and slightly turn the clinometer, and lay the box back on the plane while aligning the edge with the line. If the clinometer is not centered, repeat these steps several times until the clinometer is leveled while the edge of the box is parallel to the line, and the circle behind the compass is completely lying on the plane. This is a trial and error process that requires some practice to master.

Using the compass as hand level on a Jacob Staff
The compass can be used as hand level, mounted on a Jacob Staff to measure the true stratigraphic thickness of a lithostratigraphic unit (e.g., member, formation) as follows. Measure the true dip of the layers and set the clinometer at that angle. Mount the compass vertically (as in reading the plunge) on the Jacob Staff with the lid half closed; making sure that the clinometer is set at the measured dip angle. Start at the lower contact of a stratigraphic unit. Tilt the staff in the direction of the dip of the beds, and look inside the mirror until the clinometer level is centered. At this position, look through the sighting tip and through the sighting window. Identify a point (e.g., a brush, a piece of rock) on the ground where the line of sight intersects the ground. Move the base of the Jacob staff to that point. Use a counter and register the number of times (n) it takes to go from the basal contact of the lithostratigraphic unit to its top. At the upper contact, multiply the length of the Jacob Staff,
which is 1.5 meter, by ‘n’, to get the true stratigraphic thickness of the unit.

**Measuring the attitude of planes**

If the plane is flat, smooth, and non-magnetic, the easiest way to measure the strike and dip of the plane is to touch the edge of the box (not all the rectangular side!) with the plane while centering the circular, bull’s eye level. This will generate a horizontal line parallel to the edge of the box on the plane of interest. We have the freedom of reading either of the two needles; it does not matter which one we read! (e.g., 140° and 320° are the same strikes). This is the strike of the plane; we can mark the strike line on the plane with a pencil drawn parallel to the edge of the box. In special cases such as when taking oriented samples of rock for structural analysis, we need to distinguish and mark only one of these two ends of the horizontal line with an arrow (preferably with half arrow tip).

After the strike is measured, the magnitude of the dip of the plane is measured by putting the entire rectangular side of the box perpendicular to the strike line and centering the clinometer level. The general, dominant direction of the dip is identified geographically by checking the down-dip direction (by centering the bull’s eye level and finding out where the principal geographic directions are). In North America, the format is strike, dip and dip direction (e.g., 050°, 30° NW), because that is the sequence of measuring the attitude of a plane with the Brunton compass. Silva and other similar compasses allow easier measurement of the dip direction before or without identifying the strike direction. Thus, in Europe and other places, the format may be dip amount, dip direction, which is a vector (e.g., 30°, 320°).

If the plane of interest is not flat, and lies in front of us at the level of our line of sight, we must use eye-level sighting as follows. Stretch the sighting arm and bend the sighting tip. Close one of the eyes, and move sideways while looking onto the edge of the inclined plane. Stop moving if further moving exposes the surface of the plane. In this position, we are looking edgewise along the plane. Fold the compass lid until we see the edge of the inclined plane in the sighting window through the lid. Hold the compass as follows: Put the two thumbs under the sighting arm on the box; the two index fingers on the edge of the lid, and the center fingers behind the horizontally positioned box. Adjust the lid with the index fingers until the bull’s eye level is apparent in the mirror. Center the bull’s eye level, and intersect the edge of the plane with the black line in the sighting window (don’t try to align the black line with the edge (because it tilts the box) unless the plane is vertical). Hold your breath, and read the bearing indicated by the black or white needle (whichever is apparent in the mirror), that is, the strike of the plane in the mirror without moving the box or going off level. While in the same position, read the amount of dip by aligning the flat edge of the box with the edge of the plane. Determine the direction of the dip by inspection; give the principal direction of inclination from the geographic space as described above.

If the plane of interest is vertical and the terrain is horizontal (a special case), stand directly above the edge of the plane and read the trend of the edge of the plane as the strike. Some inexperienced geologists assume that they can determine the strike of an inclined, non-vertical plane in this way. The technique of standing above the edge of a plane does not work if the plane is non-vertical and/or the top surface is not horizontal. This is because the intersection of a non-vertical plane and non-horizontal plane is not a horizontal line, and thus cannot be a strike! In such cases, we need to directly measure the strike by either eye-level sighting or by touching as described above.

**Measuring the bearing of a line between two points**

Commonly we want to measure the trend and plunge of a line connecting two points, e.g., a line connecting a person and another person, or another landmark (e.g., house, tower, smoke stack). To do this we can either use the eye-level or waist-level sighting. The eye-level sighting was described above. For the waist-level sighting, we put the lid against our body, and tilt the lid while holding the box horizontally by centering the bull’s eye level. Position the target on the black line on the mirror, and after centering the round level, read the trend.

Measure the plunge of this line as follows. Flip the compass (box is vertical) while the lid and sighting arm are folded. Look through the hole in the sighting tip and through the sighting window, and then center the clinometer level while shooting to a specific point on the target. If the two persons have the same height, intersect the other person’s eyes with the black line on the sighting window. If we are sighting (shooting) to another person who is shorter than we are, say by 5 cm, then we shoot 5 cm above that person’s eye level (at forehead or head level). If the other person is taller by 5 cm, then we shoot to the mouth level of that person.
Measuring the attitude of a plane with the two-line technique

The two-line technique is a very useful and precise method of measuring subhorizontal and gently dipping planes. Such low-dip planes are very common, and cannot accurately be measured by measuring the strike and dip. If the exposed surface of a plane is small, we drop two sharpened pencils on the plane at high angles to each other. Point the sharp ends of the pencils down-plunge. Measure the trend and plunge of the two lines ($l_1$ and $l_2$). If the subhorizontal plane is large and extensive (e.g., a basalt layer), we define two long lines with two persons. The two persons stand at two points and shoot at each other to determine the trend and plunge of the line connecting them ($l_1$). Take the average of the two readings. They repeat this for a second line by constructing a second line ($l_2$). To determine the orientation of the plane that contains the two lines, plot the lines as two points on the stereonet, and align them on the same great circle. Read the strike and dip of the great circle.

Although the two-line technique is the best way to determine the attitude of subhorizontal or gently dipping layers, the attitude of small, gently dipping planes (e.g., bedding at the hinge zone of a mesoscopic folds) can be determined by trial and error as follows. Measure the dip of the layer where we think is near the maximum inclination (true dip); center the clinometer level. Remember the dip value. While the rectangular side of the box is still completely touching the layer, slowly turn the compass and reread the dip. If the dip is less than the previous reading, then we are going away from the maximum inclination, and our previous reading was closer to the true dip. Move toward the first position and go to the opposite direction. Repeat the process until we identify the maximum inclination which is the true dip. When the true dip orientation and magnitude is registered, measure the strike of the plane perpendicular to this line.

Using the compass for the two-point problem

Sometimes we may be located at a contact of a horizontal layer (e.g., a basalt layer or a bed) on a hill, and be interested to locate a point of the same elevation on an adjacent hill. To do this, we set the clinometer at the 0° mark, and flip the compass sideways (vertically) as described for measuring the plunge. Look through the hole of the sighting tip, through the sighting window, and center the clinometer level (which is set to 0°) by moving the box up or down and looking in the mirror (without turning the clinometer). When the level is centered, locate a point on the other hill at the intersection of your line of sight and the ground. That point has the same elevation as the point of our position.

This technique is also handy in determining the strike of a layer. Just set the clinometer at the 0° mark; stand on the layer, look along the layer, and center the clinometer without turning the clinometer. After the level is centered, locate a point on the sloping layer along your horizontal line of sight. Now that we know the strike line (the horizontal line), we need to read its bearing either by eye-level or waist-level sighting. While in the same position, read the dip of the layer across the strike line using the clinometer as described for measuring the dip.

REFERENCES

35th ANNUAL FIELDTRIP: ROAD LOG

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Unit descriptions are taken from Kath and Crawford (this volume)

Day 1, Saturday, October 6, 2001:

MILEAGE DESCRIPTION

0.0  Ramada Inn. Exit parking lot; turn right on Leland Drive.

0.10  Turn right on Windy Hill, stay in right lane.

0.25  Exit to I-75 South.

1.00  Intermediate access shaft on the right.

1.10  Exit I-285 West.

4.60  Exit South Atlanta Road; turn left on South Atlanta Road.

6.70  Exit Elizabeth Lane; turn left.

6.80  Pumping Shaft on right; sewage treatment facility (STOP 1 for Sunday, October 7, 2001). Continue along Elizabeth Lane.

7.0  Elizabeth Lane (Tunneling Machine) Access Shaft on right.

7.20  Park under power line. CAUTION – TRAIN.

Note: Fresh Unit 1 rock available as road dressing in parking area.

STOP 1. UNIT 1A AND 1C

ROCK UNIT 1A
Mylonite, composed of sericite, quartz, and feldspar; extremely fine-grained; foliation is poorly developed and very contorted; dark gray, light gray, and white in outcrop; yields uniform fine clayey residuum, buff to pale red.

The uniform fine grain size, uniform composition, and poorly developed contorted foliation all inhibit weathering; however, the abundance of feldspar enhances weathering. Combined, these characteristics result in a generally moderate and uniform depth of weathering.
CRAWFORD AND KATH

ROCK UNIT 1B (NOT EXPOSED AT THIS OUTCROP)
Mylonitized granite, composed of muscovite, quartz, and feldspar; much of the feldspar is pink and coarse-grained. Shearing was pervasive and produced a well-developed shear foliation. Reduction in grain size was not as extreme as in Rock Unit 1A; light colored; cream buff, pink.

Where shear foliation is absent or poorly developed, this rock unit is massive, with few discontinuities, and shallow weathering. The development of a shear foliation in parts of the granite has provided discontinuities which weakened the rock and allowed more rapid weathering, resulting in tabular zones of deeper, more intense weathering.

ROCK UNIT 1C
Mylonite, mylonitic button schist and mylonitic biotite gneiss; all interlayered on a scale of inches, feet, and 10’s of feet. The mylonite is composed of sericite, quartz, and feldspar, extremely fine-grained, with a poorly developed foliation. The mylonitic button schist is composed primarily of fine sericite, muscovite, quartz, and feldspar; with medium- to coarse-grained muscovite forming distinctive “eyes”; there is a well-developed shear foliation. The mylonitic biotite gneiss is composed primarily of biotite, quartz, and feldspar, very fine-grained; with a well-developed shear foliation.

Even though there are considerable differences in the mineralogy of these interlayered lithologies, the overall fine grain size seems to be the dominant control on weathering. As in Rock Unit 1A, this results in generally moderate and uniform depths of weathering.

Rock Unit 1A and Rock Unit 1B were observed in a current excavation at the Clayton Treatment Plant south of the Chattahoochee River, but may not be encountered in the Cobb Tunnel/Shaft.

Rock Unit 1C is dominant at the proposed shaft location and tunnel alignment north and west of the river, and may be the only part of Rock Unit 1 encountered in the Cobb County work.

7.70 Board busses and return to South Atlanta Road. Turn right on South Atlanta Road.

8.20 Plant Atkinon/Log Cabin Road. Saprolite of Unit 1 – Unit 2 contact.

8.60 Turn right into Vinings Storage parking lot.

STOP 2. UNIT 2
ROCK UNIT 2
Sphene-epidote-biotite-quartz-feldspar gneiss, medium- to coarse-grained; very felsic; yields light-colored soil; foliation is moderately well-developed.

Near its contact with Unit 1 and for several hundred feet to the northwest, this gneiss is extremely sheared, with a very close-spaced and well-developed shear foliation. Shearing decreases toward the northwest.

Rock Unit 2 is massive and uniform, with general shallow to moderate weathering. Along shear zones and joints weathering has proceeded to greater depth.
Turn right out of parking lot; continue on South Atlanta Road.

8.90  North Church Lane; turn right.
9.06  Log Cabin Drive; turn right.
9.40  Woodland Brook Drive; turn right.
9.5  Railroad crossing.
10.50  Orchard Knob Drive; turn left.
10.70  Randall Farm Road; turn right.
11.00  Contact between Unit 2 and Unit 3.
11.10  Ultramafic boulders of Unit 3 in yard on the left. Continue.
11.25  Road forks, bear left.
11.35  New Paces Ferry Road; turn left.
11.40  Unit III; good exposures. Continue.
11.60  Tanglewood Drive; turn left. Now in Unit 5.
11.80  Courtyard of Vinings Entrance on left. Turn left.
11.85  T-intersection; turn right.
11.90  T-intersection; turn left.
11.95  Cross street and turn right; park in Cull-de-Sac. STOP 3

STOP 3. CONTACT BETWEEN UNITS 3 AND 4
ROCK UNIT 3
Between Rock Unit 2 and Rock Unit 4, there is a mixture of lithologies which changes character along strike and, probably, down-dip.

Within this sequence are:
1) Garnet-kyanite-feldspar-muscovite-biotite-quartz schist, fine- to coarse-grained; very quartzose, in part.
2) Garnet-kyanite-muscovite-biotite-quartz-feldspar gneiss, fine- to coarse-grained; schistose in part.
3) Quartzite; medium-grained and clean in part; also fine- to coarse-grained and micaceous and/or feldspathic.
4) Amphibolite/hornblende gneiss, fine- to medium-grained.
5) Ultramafic - coarse grained pyroxene and amphibole; massive; apparently as small ovoid bodies several 10's of feet to a few 100 feet in their longest dimension.
Pegmatites and pegmatitic layers, lenses, and pods are common throughout. The quartzite was mapped separately, where feasible; grades into quartzose schist. Foliation parallel to compositional layering is well developed in Unit 3; shearing is common.

The great differences in mineral composition, texture, and discontinuities in this Rock Unit have caused considerable internal differences in weathering depths. However, the general high content of quartz and muscovite has restricted the overall depth of weathering.

The quartzites, quartzose muscovite schists, and coarse-grained ultramafics are the least weathered lithologies in this Unit; the feldspar- and biotite-rich gneisses and schists the most weathered.

The contrasts in weathering depths make this Unit potentially troublesome.

**ROCK UNIT 4**

Biotite-quartz-feldspar gneiss; quartz and feldspar are medium- to coarse-grained; biotite is fine- to medium-grained. Muscovite is present where this gneiss is sheared. Shear foliation is commonly developed. This gneiss is very felsic.

The high feldspar content, combined with the dominant mica being biotite rather than muscovite, enhances the weathering of Rock Unit 4. However, its massiveness and uniformity inhibit weathering. Consequently, weathering is rather uniform and of moderate depth except in areas of joint concentrations.

Retrace route to New Paces Ferry Road.

12.4  New Paces Ferry Road; turn left.
12.55  Paces Ferry Road; turn left.
12.60  Railroad Crossing.
13.05  Cumberland Parkway; turn left.
13.80  (Vinings Vineyard). Paces Walk; turn left.
13.85  Vinings Vineyard Apartments; turn left. STOP 4

**STOP 4. QUARTZITE OF UNIT 5**

**ROCK UNIT 5**

Rock Unit 5 is a schist/gneiss/quartzite unit, the same as Rock Unit 3. Diverse weathering characteristics of this sequence will be very similar to those of Rock Unit 3.

14.05  Return to Cumberland Parkway; turn right.
14.75  Paces Ferry; continue on Cumberland Parkway.
15.70  Railroad Overpass
15.75 Cumberland Boulevard; turn right.

15.95 KISS-RIDE CCT. STOP 5. Unload and go down to Railroad cut. CAUTION CAUTION CAUTION Reload and continue on Cumberland Boulevard.

**STOP 5. CONTACT UNIT 7 AND 8**

**ROCK UNIT 7**

Rock Unit 7 is thin, approximately 600 feet in outcrop width along the tunnel alignment, and consists of:

1) Quartzite and micaceous quartzite, fine- to medium-grained, intensely sheared; structurally overlain by:

2) Kyanite-garnet-feldspar-biotite-muscovite-quartz schist, coarse-grained, with feldspar “eyes”, and abundant concordant pegmatitic pods, lenses, and layers;

3) This schist is structurally overlain by another schist, with fewer and smaller garnets, less biotite and muscovite, and more quartz; which, in turn, is structurally overlain by:

4) A garnet (small, scarce)-biotite-muscovite-feldspar-quartz gneiss, fine-grained, well foliated and slabby; appears to have been intensely sheared and silicified.

The dominance of muscovite and quartz in this thin rock unit suggests that it will not be deeply weathered. However, it has deformed brittlely, and the abundance of joints and joint sets enhance porosity and permeability.

**ROCK UNIT 8**

Garnet (small, minor)-muscovite-biotite-quartz-feldspar gneiss, fine- to medium-grained, schistose in part; interlayered with garnet (small, minor)-biotite-feldspar-quartz-muscovite schist, medium- to coarse-grained; some garnet-rich zones; all laced with concordant and discordant pegmatite pods, lenses, and layers up to 10 feet thick; foliation wraps around pegmatite pods/lenses.

Well-developed compositional layering/foliation, two well-developed joint sets, high feldspar content, and the abundance of large pegmatites control differential weathering which will be quite deep in places. In a favorable topographic setting, groundwater potential is considerable.

16.15 Akers Mill; turn left.

16.35 Cobb Parkway; continue on Akers Mill.

16.85 I-75 Overpass.

17.05 T-intersection; turn left. Continue on Akers Mill.

17.15 Rottonwood Creek.

17.30 One Towercreek Entrance; turn left and continue to back parking lot.

17.45 STOP 6 – LUNCH. Contact between Unit 7 and Unit 8. Return to Akers Mill.

**STOP 6. CONTACT UNIT 7 AND 8**

See stop description for Stop 5
17.65  Akers Mill; turn left.
18.40  Traffic Light – Powers Ferry Road; turn left.
18.45  Interstate North Parkway; turn left.
19.60  Windy Ridge Road; continue on Interstate North Parkway.
20.05  Interstate North Parkway; turn left.
20.45  The Sporting Club at Windy Hill. STOP 7. Turn left, return to Interstate North Parkway; turn right.

**STOP 7. UNIT 13**

**ROCK UNIT 13**
Hornblende gneiss/amphibolite, thinly laminated fine- to medium-grained hornblende and plagioclase; and garnet-biotite-feldspar-quartz-muscovite schist, coarse-grained, button texture, with abundant fine disseminated black opaques; interlayered on a scale of feet and 10’s of feet. Foliation orientation is highly variable over short distances. Outcrop width along the tunnel alignment is approximately 800 feet.

The amphibolite/hornblende gneiss of Rock Unit 12, and the amphibolite/hornblende gneiss interlayered with schist of Rock Unit 13 have the potential for large groundwater yields. Their mineralogy and abundance of joints make them susceptible to weathering. In addition, their structural position between underlying and overlying muscovite- and quartz-rich schists make them a relatively easy surface-water and groundwater pathway.

20.70  Unit 13
21.10  Interstate North Parkway West; turn right.
21.25  Wellesley Inn & Suites; turn right.
21.30  Turn left; uphill to left.
21.45  STOP 8 – Papasitos Cantina
   Unit 14

**STOP 8. UNIT 14 BUTTON SCHIST**

**ROCK UNIT 14**
Garnet-biotite-muscovite-quartz schist, coarse-grained, with thickly disseminated fine black opaques; muscovite is generally coarser-grained than biotite; sheared, button texture. Joints are poorly developed and scarce; shallow-weathering. Outcrop width along the tunnel alignment is approximately 400 feet.

An abundance of muscovite and quartz combined with poor joint development has caused depth of weathering to be shallow and groundwater potential to be low.
Return to Interstate North Parkway West.

21.75  Windy Hill; turn left.

21.85  I-75 Overpass.

22.70  Cobb Parkway; turn right.

23.15  Airport Industrial Park Drive; turn left.

23.70  Cull-de-Sac – STOP 9.

STOP 9. UNIT 15
ROCK UNIT 15
Garnet-muscovite-biotite-quartz-feldspar gneiss, fine- to medium-grained, and garnet (common to abundant)-feldspar-quartz-muscovite-biotite schist, medium- to coarse-grained, interlayered; and all extensively pegmatized with coarse-grained muscovite-quartz-feldspar. Micas in the schist are often coarse-grained and in part oriented across the compositional layering creating a “tough” rock which resists breaking. This rock unit is very non-uniform. It weathers unevenly, and often in non-planar directions. Where compositional layering and foliation are well developed, differential weathering produces a slabby outcrop. The thickness of weathering residuum varies from thin to thick over short distances; and thick residuum often contains large bouldery masses of relatively fresh rock. Small, apparently ovoid bodies of biotite-quartz-feldspar granite, medium- to coarse-grained, equigranular, massive, without foliation or with only a poorly developed foliation, are scattered in this unit.

Depth of weathering and groundwater potential are quite variable. Favorable structural and topographic positions will yield large volumes of groundwater.

Return to Cobb Parkway

24.25  Cobb Parkway; turn right.

24.50  Terrell Mill; turn left.

25.25  I-75 Underpass.

26.15  Powers Ferry Road.

26.65  Delk Road. on left; bear right on Terrell Mill Road.

27.65  Paper Mill Road. Continue on Terrell Mill Road.

28.15  Lower Roswell Road. Continue straight ahead.

29.25  Cross Gate; turn left.

29.55  “Stub”; turn right. STOP 10.
STOP 10. UNIT 16
ROCK UNIT 16
Biotite-quartz-feldspar gneiss, fine- to medium-grained, schistose in part; biotite-hornblende-feldspar gneiss, fine- to medium-grained; and amphibolite, fine- to medium-grained; all are interlayered or intermixed. Together, and in approximately equal parts, these three lithologies make up greater than 90 percent of this rock unit. The rock weathers to a yellow-brown, pink, or brownish gray saprolite/residuum. The remaining part of this lithologic unit consists of small medium- to coarse-grained mafic and ultramafic bodies, apparently ovoid and several feet to a few hundred feet in their longest dimension, and muscovite-quartz-feldspar pegmatites as much as 8 to 12 feet thick. This rock unit weathers deeply to a soft, feldspathic residuum, except for the coarse-grained mafic and ultramafic bodies and the pegamites. The coarse-grained mafics yield a hard, tough saprolite with well-developed boxwork; and pegmatites are present in residuum as resistant boulders.

Like Rock Unit 15, this rock unit contains small, apparently ovoid, bodies of biotite-quartz-feldspar granite, medium- to coarse-grained, equigranular; massive, without foliation or with only a poorly developed foliation. Only one small body was noted along the tunnel alignment in this unit; there may be others.

The biotite and feldspar content of Rock Unit 16 has allowed deep weathering and lots of groundwater storage. The variability of its lithologies and the pervasive large pegmatites enhance the potential for groundwater. Expect large volumes at sites with favorable structural and topographic settings.

There should be little water in the small granite bodies of Rock Units 15 and 16.

Return to Lower Roswell Road.

29.85 Turn right; retrace route to Powers Ferry Road.
32.85 Turn left on Powers Ferry Road.
33.75 Windy Hill Road; turn right.
34.20 Leland Drive; turn right.
34.3 Left turn into the Ramada.

END OF DAY 1
Day 2, Saturday, October 6, 2001:

MILEAGE DESCRIPTION

1.0 Ramada Inn. Exit parking lot; turn right on Leland Drive.
0.11 Windy Hill; turn right.
0.26 Exit to I-75 South.
1.00 Intermediate Shaft on the right.
1.10 Exit I-285 West
4.60 Exit South Atlanta Road; turn left on South Atlanta Road.
6.71 Exit Elizabeth Lane; turn left.
6.81 Pumping Shaft on right; sewage treatment facility (Stop 1 for Sunday, October 7, 2001). Continue along Elizabeth Lane.
8.0 Elizabeth Lane (Tunneling Machine) Access Shaft on right. Turn right into parking lot.

STOP 1. UNIT 1A AND 1C

ROCK UNIT 1A
Mylonite, composed of sericite, quartz, and feldspar; extremely fine-grained; foliation is poorly developed and very contorted; dark gray, light gray, and white in outcrop; yields uniform fine clayey residuum, buff to pale red.

The uniform fine grain size, uniform composition, and poorly developed contorted foliation all inhibit weathering; however, the abundance of feldspar enhances weathering. Combined, these characteristics result in a generally moderate and uniform depth of weathering.

ROCK UNIT 1B (NOT EXPOSED AT THIS OUTCROP)
Mylonitized granite, composed of muscovite, quartz, and feldspar; much of the feldspar is pink and coarse-grained. Shearing was pervasive and produced a well-developed shear foliation. Reduction in grain size was not as extreme as in Rock Unit 1A; light colored; cream buff, pink.

Where shear foliation is absent or poorly developed, this rock unit is massive, with few discontinuities, and shallow weathering. The development of a shear foliation in parts of the granite has provided discontinuities which weakened the rock and allowed more rapid weathering, resulting in tabular zones of deeper, more intense weathering.
**ROCK UNIT 1C**
Mylonite, mylonitic button schist and mylonitic biotite gneiss; all interlayered on a scale of inches, feet, and 10’s of feet. The mylonite is composed of sericite, quartz, and feldspar, extremely fine-grained, with a poorly developed foliation. The mylonitic button schist is composed primarily of fine sericite, muscovite, quartz, and feldspar; with medium- to coarse-grained muscovite forming distinctive “eyes”; there is a well-developed shear foliation. The mylonitic biotite gneiss is composed primarily of biotite, quartz, and feldspar, very fine-grained; with a well-developed shear foliation.

Even though there are considerable differences in the mineralogy of these interlayered lithologies, the overall fine grain size seems to be the dominant control on weathering. As in Rock Unit 1A, this results in generally moderate and uniform depths of weathering.

Rock Unit 1A and Rock Unit 1B were observed in a current excavation at the Clayton Treatment Plant south of the Chattahoochee River, but may not be encountered in the Cobb Tunnel/Shaft.

Rock Unit 1C is dominant at the proposed shaft location and tunnel alignment north and west of the river, and may be the only part of Rock Unit 1 encountered in the Cobb County work.

**END OF DAY 2**
<table>
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<tr>
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<td>Geology of the Barnesville area and Tonaliga Fault, Lamar County, Georgia.</td>
<td>by W. H. Grant.</td>
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