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Abstract

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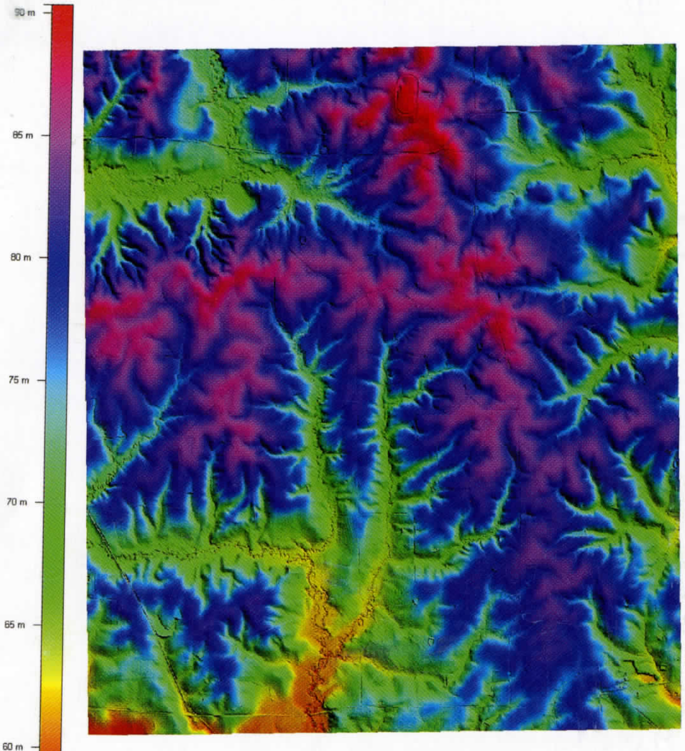
SOUTHEASTERN GEOLOGY



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The Stream Net as an Indicator of Cryptic Systematic Fracturing in Louisiana

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ABSTRACT

The stream net in many parts of Louisiana includes straight reaches with preferred alignment in a few directions, with some examples spanning tens of kilometers. In places the reaches form classic rectangular drainage patterns. These characteristics are obvious on maps at a variety of scales, and are recognizable on some portion of nearly every 7.5-minute quadrangle in the state, excepting those quadrangles situated entirely within the Holocene coastal marshes or the Holocene flood plains of the larger rivers. Such patterns of lineaments are reminiscent of patterns associated with systematic fracturing in other regions. In Louisiana, however, verification and measurement of fractures that may exist in the vicinity of rectilinear drainage anomalies is problematic because surface deposits are comparatively young and sparsely exposed, and tend, especially near waterways, to be heavily weathered and vegetated. An indirect approach to evaluating the potential influence on drainage by fracturing involves evaluating the frequency distribution of stream-course orientations based on its degree of similarity with that of the strikes of previously mapped or reported fractures (faults and/or joints).

A rose diagram of orientation frequencies for the stream net of the entire state, created utilizing a publicly available line dataset processed into 100-m segments (N | 290,000), shows a nonrandom distribution with three visually identifiable trends: the strongest, oriented essentially N-S; a subsidiary trend oriented N20°–30°W; and a weak trend oriented N80°–90°W. The entire population of orientations yields a mean direction of N17.5°W ± 4.2° with a probability of 95 percent. The strike frequencies of mapped faults show little correspondence with these trends. This suggests, if mapped faults are at least representative of actual faults, that insofar as apparent lineaments reflect structure and not the influence of a south-southeasterly regional drainage gradient, they predominantly reveal the influence of joints. These could reflect either a Quaternary stress regime, or propagation in young sediment of a structural pattern in underlying older strata. The data available at present do not compel either interpretation, though in south Louisiana at least, where reactivated early Tertiary growth faults have surface expression that in places is juxtaposed with differently oriented drainage lineaments, propagation of a preexisting pattern from depth appears plausible. Widespread systematic fracturing in this predominantly Quaternary coastal-plain setting could have important implications for groundwater flow and for other processes that depend substantially on permeability.

INTRODUCTION

A diverse literature chronicles perceptions and interpretations of lineaments. A number of investigations of the late 19th to mid 20th centuries, of which Gay (1973) and Katterfeld (1976) give brief reviews, reported observation of essentially orthogonal sets of lineaments, and inference of the existence in the Earth's continental crust of corresponding planar structures.

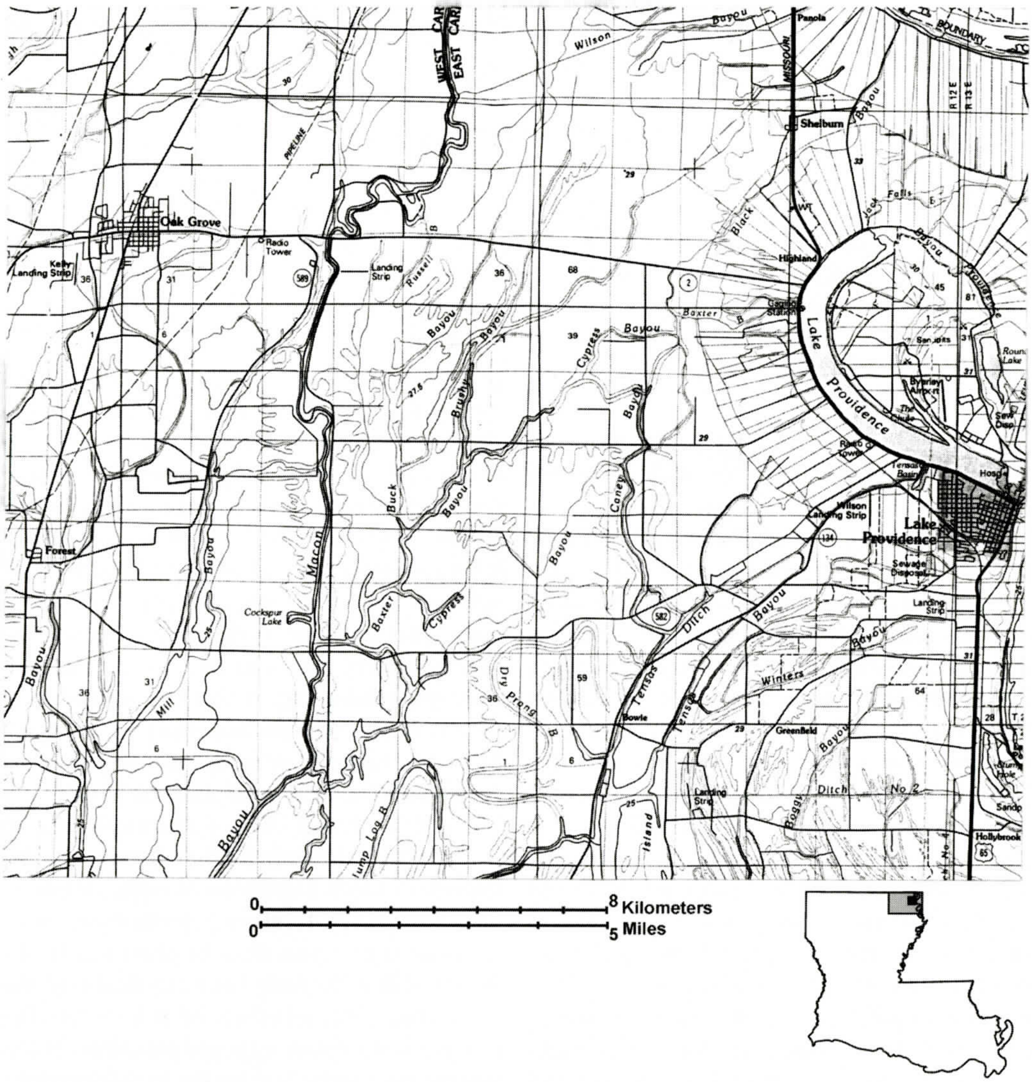

Figure 1. Area (solid black) between Oak Grove and Lake Providence, in the northeastern portion of the Bastrop 1:100,000-scale topographic quadrangle (shaded), northeastern Louisiana. Drainage-course segments suggestive of lineaments, delineated by stream courses and associated elevation contours in the middle of this image, occur entirely in Holocene sediment at the western edge of the Mississippi River flood plain between late Pleistocene, braided glaciofluvial outwash deposits on the west, and Mississippi River meander-belt deposits on the east. (Mill Bayou, west of Bayou Macon, follows the contact separating Holocene alluvium from the terraced late Pleistocene outwash deposits to the west.)

Such interpretation has typically assumed that rectilinear drainage patterns reflect a structural influence on drainage, but is controversial because of the subjective manner by which the drainage patterns have been recognized. Less commonly, fracturing is well documented and then correlated with drainage (e.g., Stauffer and Gendzwill 1987). One practitioner inferring "pervasive orthogonal fracturing" as the cause of surface and subsurface lineaments has been Gay (1972, 1973, n.d.), who interprets fracturing as an ancient pattern propagated into younger sediment from depth. Alternatively, Stauffer and Gendzwill (1987) postulated a mechanism for contemporaneous production of NW- and NE-striking joints in the midcontinent of North America.

Scheidegger (1980) took an indirect approach to the problem of recognizing structural influence on drainage, by summing the orientations of segments of stream (valley) courses in two drainage basins in the Alps and one in the Canadian Arctic, and comparing the results with directional data for structures in those areas. He found nonrandom frequency distributions characterized by maxima that in the alpine basins correlated with the strike-frequency maxima of measured joints, and concluded that orientations of valleys and strikes of joints in the Alps express the orientation of the neotectonic stress field.

The present exercise examines the orientation frequency of Louisiana stream segments for analogous nonrandom character, for comparison of apparent preferred orientations with the preferred strike of mapped or reported fractures (faults and/or joints). The stream net in many parts of the state clearly shows, on maps at a variety of scales, courses with straight reaches that show preferred alignment in a few consistent orientations. The largest rectilinear examples span tens of kilometers, and in some areas stream reaches form classic rectangular drainage patterns. More significantly, rectilinear characteristics show widespread occurrence, and may be discerned on some portion of nearly every 7.5-minute quadrangle in the state, excepting those quadrangles lying entirely within the coastal marsh or the flood plains of the larger rivers, i.e., those underlain exclusively by Holocene sediment. Yet even in such settings, rectilinear stream-course segments may occur in places (Figure 1). Such features are reminiscent of those observed in systematically jointed and faulted terranes in other regions, including areas interpreted as influenced by basement structure. In Louisiana, however, checking for fractures is difficult near rectilinear drainage anomalies because surface deposits are sparsely exposed and tend to be heavily weathered and vegetated near waterways. This difficulty prompted the trial of an approach to the problem similar to that of Scheidegger (1980).

An earlier examination of apparent nonrandom frequency distributions in the orientations of drainage courses in Louisiana (McCulloh 1995) utilized primarily drainage lineaments formed by *alluvial* courses (alluvial bottoms)—as defined by undifferentiated Quaternary tributary alluvium recompiled from various sources at 1:500,000 scale (his figure 4)—rather than stream courses (channels) *per se* (Figure 2 contains examples of alluvial courses forming such lineaments on newer mapping done at 1:24,000 scale). Other map information of various types, scales, and sources was also included, to illustrate selected exemplary lineamentlike features known to the author at the time. One consequence of this approach, inclusive in some respects (data type and source) and selective in others (geography), was that the data reviewed and summarized were neither of consistent character and quality nor uniformly distributed across the state. So one goal of the present exercise was to maximize data and process consistency by summarizing the orientations of stream courses statewide, using a single publicly available hydrographic data set and analyzing it with an application that works within a standard Geographic Information System (GIS) software program.

The earliest interpretation of lineaments in Louisiana appears to have been Fisk's (1944) mapping of drainage lineaments; analogous work was carried out in Florida by Vernon (1951). These investigations portrayed a rectilinear grid consisting of a single pair of nearly orthogonal lineament sets, oriented NE-SW and NW-SE, in the Mississippi embayment and southeastern U.S. Fisk (1944) referred to his interpreted lineaments as fault zones (cf. his figure 6), or collectively as a regional fracture pattern (cf. his figure 71), and even assigned proper names to the more prominent trends. In north Louisiana, at least, Fisk's (1944) lineaments are neither coincident with the drainage lineaments interpreted at a scale of 1:500,000 by McCulloh (1995, his figure 4), nor with the inferred wrench-fault zones of Zimmerman

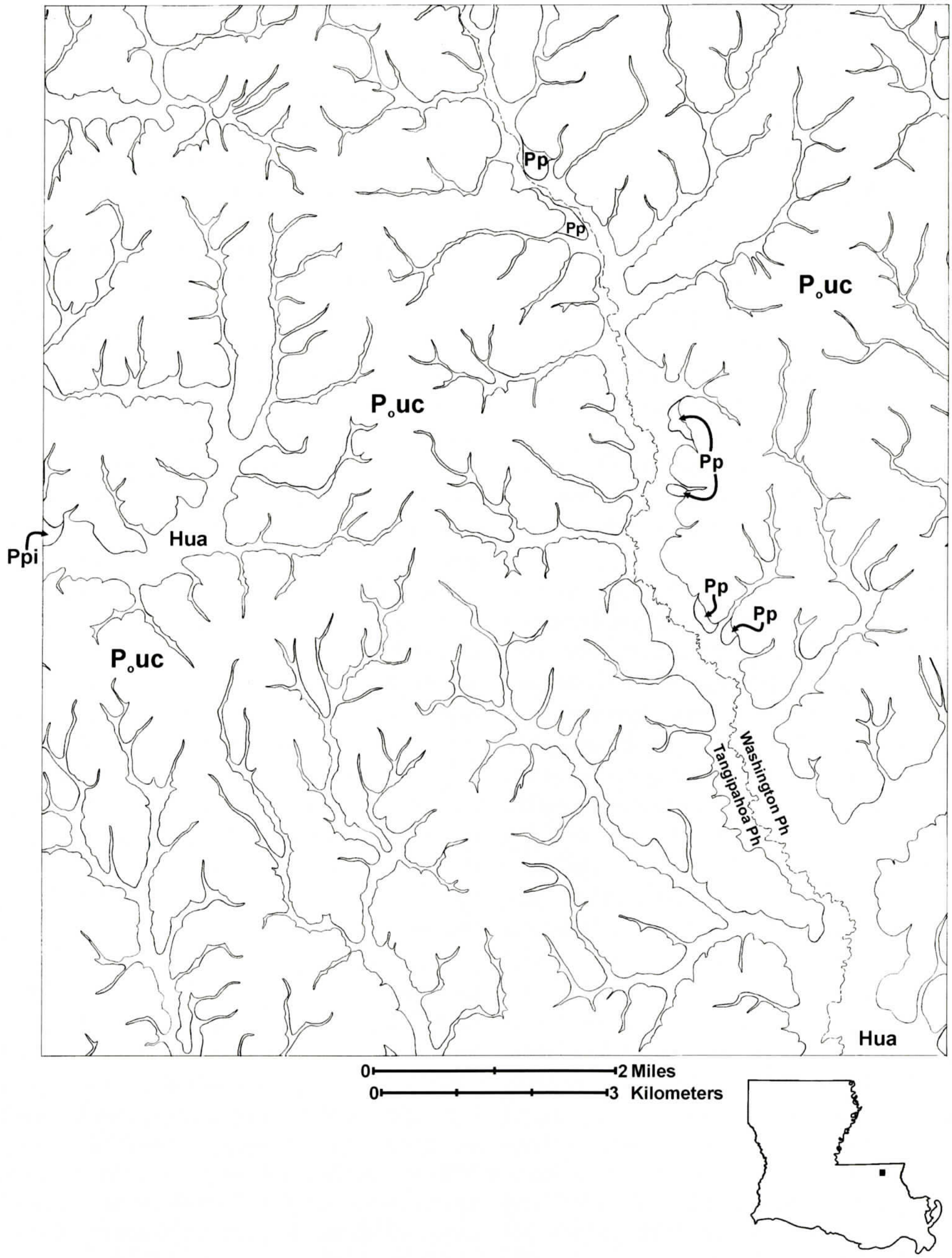

Figure 2. Surface geology of the Wilmer 7.5-minute quadrangle, northeastern south Louisiana, showing drainage lineaments formed by alluvial-course segments (alluvial bottoms). The lineaments resolve as two pairs of sets, with each pair consisting of essentially orthogonal elements that constitute the diagonals to the other pair of sets (i.e., N-S-E-W and NE-SW-NW-SE). $P_o$uc = Pliocene Upland allogroup, Citronelle Formation; Ppi = Pleistocene Prairie Allogroup, Early Sangamon, Irene alloformation; Pp = Pleistocene Prairie Allogroup, undifferentiated; Hua = Holocene undifferentiated alluvium. Geologic mapping by the author, of one of 32 source maps recompiled in 1:100,000-scale quadrangle format by McCulloh and others (1997).

(1992, 1994, 1996). In south Louisiana, however, the drainage lineaments of Fisk (1944) and those later mapped by Birdseye and others (1988) show essentially identical orientation-frequency maxima (cf. figure 17 of Gay 1973 and figure 5 of McCulloh 1995).

The variously interpreted surface lineaments in Louisiana occur entirely in Cenozoic, predominantly Quaternary coastal-plain sediment, and none has yet been found clearly coincident or correlative with an independently mapped surface fault. Although published data pertaining to joints in Louisiana are sparse, joints have been inferred as the likely control of drainage lineaments in portions of eastern south Louisiana by Birdseye and others (1988), in portions of north Louisiana by Russ (1975) and Washington and Strickland (2000), and statewide by McCulloh (1995). In the previous examination of Louisiana drainage-course orientations, McCulloh (1995) correlated the strike of the primary joint set measured at each of three localities in a single small area in west-central Louisiana (Longleaf Vista, in the Red Dirt Wildlife Management Area) with the orientations of nearby stream courses. Thus far, however, obvious correlation of the strikes of multiple joint sets with orientations of analogously arrayed drainage lineaments has been rare. In recent areal mapping of the surface geology of a ten-quadrangle area in west-central Louisiana (McCulloh and Heinrich 2002), joint strikes measured at each individual locality in Miocene strata showed two predominant directions, but these varied among the localities, and the data could neither be consistently summarized nor related to rectilinear drainage patterns. At one locality the joints observed included some (Figure 3) arrayed similarly to the drainage lineaments shown in Figure 2, though only one of the sets, striking N-S, corresponds to a maximum for the entire population. Recently in north Louisiana, Washington and Strickland (2000) correlated stream-course orientations with three joint sets striking N10°E, N60°E, and N80°W, and inferred control of the streams by the joints.

A substantial difference between the present exercise and that reported by Scheidegger (1980), apart from the coastal-plain setting, is the larger study area encompassing multiple drainage basins. Additionally, no inference is here made relative to the neotectonic stress field, because accurate strain measurements for Louisiana are not yet publicly available, and because of the potential in this Gulf–margin setting for surface expression of older structures (Zimmerman 1992, 1994, 1996; cf. Gay 1973). However, this exercise should permit comparison with comprehensive data on the current stress field affecting Louisiana as such data become available, and ultimately bear on the question of whether streams reflect control by neotectonic or older structures.

The multi-basin study area risks a decrease in resolution of patterns that may be well resolved in smaller areas, unless identical patterns manifest in all the different drainage basins. Additionally, the relative sparsity of measured joint strikes for the state as a whole necessitates comparison mainly with mapped faults rather than with joints—despite suggestions that joints are the probable primary control on nonrandom stream-course orientations (Birdseye and others 1988; McCulloh 1995; Washington and Strickland 2000), and indications that Louisiana's mapped surface faults reflect variable recognition criteria and may represent a notably conservative rendering of actual faults, owing largely to problems of surficial cover. With the above provisos, what follows is an attempt at obtaining a first assessment of the principal orientation frequencies of Louisiana streams, and of the extent of their correspondence with the strikes of known structures.

VISUAL RECOGNITION OF RECTILINEARITY

As used herein, *rectilinear drainage* refers to a pattern characterized by relative straightness and parallelism—including especially parallelism of tributaries of the same trunk stream—and would ideally include tributaries with oppositely directed flow (Figure 4).[1] It includes the classically defined rectangular pattern, as well as a sawtooth or zig-zag pattern of a tributary or trunk stream. Depending on the types of map information being considered, there are poten-

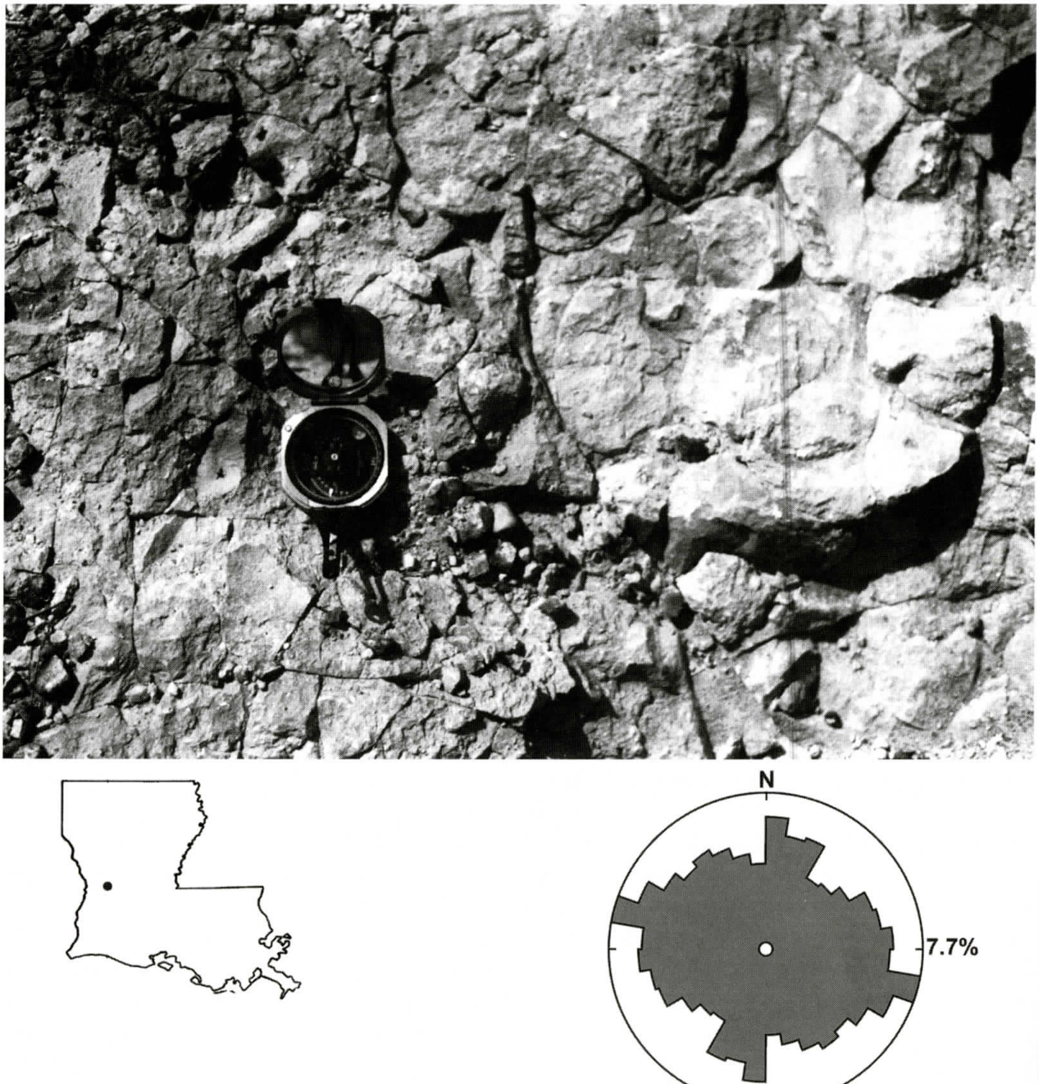

Figure 3. Photograph of joints arrayed similarly to the drainage lineaments of Figure 2. Joints are in gray, moderately indurated, very fine sandstone of the Blounts Creek Formation of the Miocene Fleming Group, at a heavily jointed locality in the Fort Polk region, west-central Louisiana (Big Creek area, EC Sec. 21, T. 1 N., R. 7 W, in the west-central ninth of the Birds Creek 7.5-minute quadrangle). Joints shown include sets with northerly, easterly, northeasterly, and northwesterly strikes. Brunton compass is placed within a square formed by N-S and E-W joints and on an intersection of its NE-SW and NW-SE diagonal sets (top = south). The sets identifiable in the photograph, with one exception (striking N-S), do not correspond to frequency maxima for the entire population of joints measured at this locality (inset: rose diagram prepared with 10° intervals and 30° moving average); but the strike frequency distribution of the population, although inconsistent with a null hypothesis of randomness, does not quite attain the conventional cutoff value of significance (p = 0.05) in its deviation from random, χ^2(17, N = 190) = 26.566, p = 0.0647. [In Louisiana the Fleming, though traditionally classified as a formation, is more appropriately described as of group rank and consisting of formation-rank subunits. Following the suggestion of Rogers (1999), it was so designated for the investigation of surface geology (McCulloh and Heinrich 2002) during which this photograph was taken.]

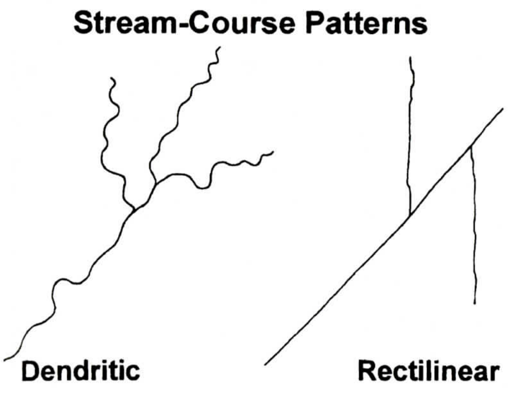

Figure 4. Idealized sketch of rectilinear drainage as contrasted with dendritic drainage. Rectilinear drainage is characterized by relative straightness and parallelism, and can include the familiar rectangular pattern, as well as a sawtooth or zig-zag pattern of a single drainage course.

tially many visual cues to the two main aspects of rectilinearity. "Straightness" can include that aspect of a stream course (channel); of a relatively narrow zone occupied by a tightly meandering channel; of an alluvial course (alluvial bottom, alluvial valley); and of the valley walls of an alluvial course. "Parallelism" can refer to a relatively small number of consistent orientations of "straight" courses, or to a parallel aspect of facing, perceptibly straight valley walls. There are probably other cues as well, and in practice, a single interpreted lineament may show a number of them.

Although perception of rectilinearity amounts to simple pattern recognition, the variety of possible indicators and the differences in the way observers may perceive them can increase the difficulties attending the subjectivity of the perceptions rather than the level of confidence. Where enough "rectilinear" attributes occur in conjunction, a given observer will perceive this as meaningful; but the perception may not be identical for any two observers. Apart from problems of observer inconsistency, the areal separation of dendritic from rectilinear drainage patterns in many geologic settings, as Melton (1959) observed, is in practice essentially impossible because the two types are "intimately and irregularly intermingled" (p. 361). Figures 2 and 5 suggest that the Louisiana Gulf Coast is such a setting, with drainage patterns presenting a variable blend of rectilinear and dendritic attributes.

The value of visual recognition of stream rectilinearity, however subjective, is as an initial indicator of apparent deviation from random, from the expected or "default" dendritic pattern, to an individual observer. According to Morisawa (1963), truly dendritic drainage does in fact closely approximate a random distribution of stream-segment orientations, but requires an extremely flat surface formed on a homogeneous substrate; and deviations from the random frequency distribution are attributable to deviations from either of these two preconditions. Either type of deviation may relate in some way to geological structure: the regional dip of strata may influence the regional drainage gradient (in a single direction), and inhomogeneity from systematic fracturing may influence drainage directions in a limited number of consistent orientations. A nonuniform orientation-frequency pattern with multiple maxima cannot be due to slope alone, and must entail some measure of inhomogeneity, the principal suspected geological cause of which would be systematic fractures. Where significance testing results are reported in this paper, they refer to the significance of a sample's deviation from randomness of orientation as characterized in this manner by Morisawa (1963), corresponding to the test of a null hypothesis of a circular uniform distribution (Davis 1986).

What is reported here certainly began as a se-

1. The term appears close in meaning to the entry for *angulate drainage pattern* given by the *Glossary of Geology* (Jackson 1997). *Rectilinear* is here given preference because it is an appropriately defined descriptive term from common English whose essential meaning is already known intuitively to many people, as well as a word that has seen at least intermittent use in the geosciences. *Angulate*, by contrast, is a genetic term, specially coined in the early 1930s, indicative of knowledge (as opposed to inference only) that streams follow faults and/or joints (Jackson 1997); additionally, it does not appear to have seen widespread or consistent use in the geosciences.

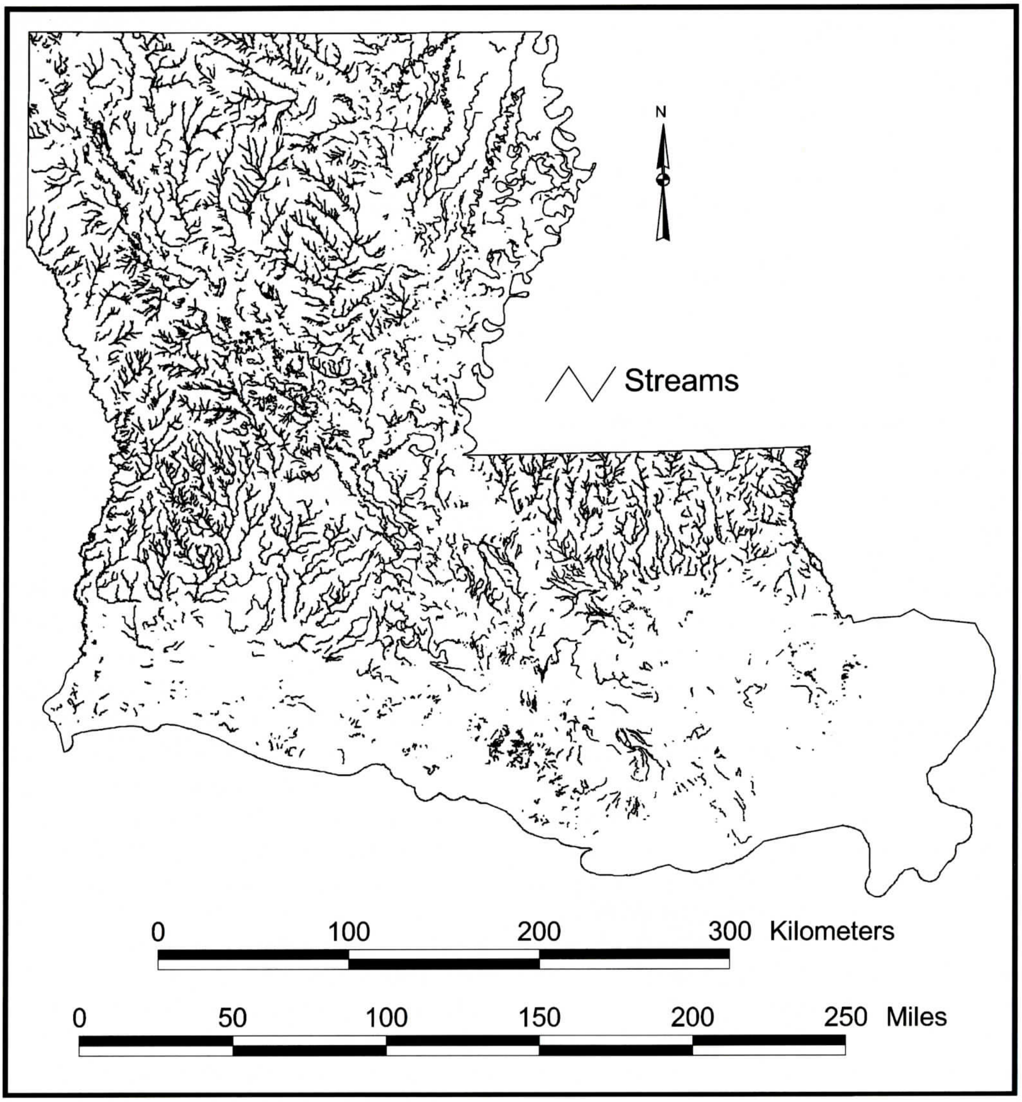

Figure 5. Plot of stream net ("Stream Drainage Hydrography" theme, NAD83) analyzed for this investigation, from the Louisiana GIS CD, version 2.0, 1999 (originator: Louisiana Oil Spill Coordinator's Office [LOSCO], 1999; source data: ESRI/GDT). The original source file excludes major rivers and the wider, more distal portions of certain other rivers; the file shown here was also modified as detailed in the text to exclude obviously artificial waterways comprising drainage canals.

ries of apparently meaningful chance perceptions. These were followed up with an attempt at more systematic observation, examples of which (Figures 1–3) yet remained anecdotal. It became essential to follow up visual recognition of rectilinearity and apparent preferred orientations with some sort of repeatable quantitative exercise, because of the limited capacity for obtaining "ground truth" in Louisiana. Again, to this end the basic technique of Scheidegger (1980) seemed an appropriate first approach to this aspect of Louisiana streams.

METHODS

The stream net for Louisiana (Figure 5) was obtained as a digital file (NAD83) from the Louisiana GIS CD, version 2.0 (Braud and others 1999). The CD's metadata file identifies this stream-net file as a line dataset derived from an Environmental Systems Research Institute (ESRI) data set "created from Geographic Data Technology, Inc. Dynamap 2000 v7.3 data that was in turn derived from the Bureau of the Census TIGER/Line files," and as constituting "a reference 'rivers' theme data set for the Louisiana Oil Spill Coordinator's Office (LOSCO)." This is the data set for the theme labeled "Stream Drainage Hydrography," and does not include major rivers and the wider, more distal portions of certain other rivers, which are placed in a separate (polygon) file for another theme labeled "Major Rivers and Lakes." Rivers thus excluded from the stream-net file used for this exercise include the Sabine, Red, Mississippi, Ouachita, Boeuf, lower Tensas, Black, Little, Atchafalaya, lower Amite, lower Tangipahoa, Bogue Chitto, and Pearl. The size (width) of these features, however, creates its own problems of interpretation, which are for the present avoided. Also thus avoided is inclusion of the major artificial waterways, such as the Intracoastal Waterway and the Mississippi River Gulf Outlet Canal, which would otherwise require elimination from the data set. Some smaller artificial waterways were, however, deleted: those comprising two small groups of obvious drainage canals, oriented in essentially the cardinal directions, in New Orleans and certain of its suburbs; and certain additional waterways whose entries in the attribute table contain the word(s) "CANAL," "DRAIN DITCH," "LAGOON," and so forth. Figure 5 is a plot of the revised stream-net file.

The minimum separation between points in the original dataset is estimated to lie in the range of 1 to 2.5 m. This is based on a stated resolution of 0.00001 decimal degrees equal to approximately 1 m, and on a digitizing resolution of approximately 0.001 inch (0.00254 cm, or 2.5 m at 1:100,000 scale). Additionally, the file includes only streams in the source data set that had names; most of the unnamed streams thus eliminated are expected to have been minor, and an overwhelming majority of them lies in the coastal zone. Finally, the minimum tributary size (length) for the Stream Drainage Hydrography theme is suggested by the shortest or lowest-importance stream included in a typical 1:100,000-quadrangle hydrographic dataset, given by the compilation standards for 1:100,000-scale quadrangle maps as equivalent to approximately 1.6 km (1 mi).[2]

A shareware program, Geotools, which functions as an extension in ArcView, was used to resolve the stream-net file into segments and determine their orientations, and to prepare a frequency histogram (rose diagram) of the results. Because the data layer file was of a size that greatly exceeded the software capabilities (owing to the overall sinuosity inherent in the courses composing the stream-net file), it had to be processed in a GIS to reduce the number of vertices and produce a layer suitable for analysis. In this simplified version of the dataset, interval distances or segment lengths were specified at 100 meters, and the number of data segments for the entire file was nearly 290,000.[3] The rose diagram plot of this version of the dataset is shown in Figure 6.

RESULTS AND DISCUSSION

The rose diagram of Louisiana stream-course orientations shows a frequency distribution with a predominant maximum oriented essentially N-S, an additional trend oriented N20°–30°W, and another, subtler trend oriented N80°–90°W (Figure 6). These trends show little correspondence with the strikes of mapped faults in the state (cf. McCulloh 1995, his figures 3 and 7): the N20°–30°W and N80°–90°W

2. In Part 3, Feature Specifications and Compilation, *Standards for 1:100,000-Scale Quadrangle Maps*, pages 3-79 through 3-82, it is stated that a stream must be at least 0.63 inch long at the map publication scale to be shown on the map.

3. The sum of the counts in the 18 class bins created by Geotools to prepare the diagram (289,356) differs slightly from the sum of total segments indicated by ArcInfo for the input data set (289,383).

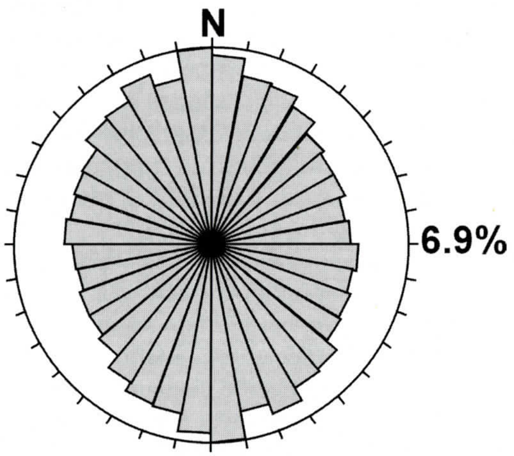

Figure 6. Orientation-frequency diagram for the Louisiana stream-net file shown in Figure 5 (10° intervals, unaveraged, N=289,383), prepared following generalization of the dataset in ESRI's ArcInfo software by specifying the minimum distance between line-segment vertices as 100 m. (Diagram prepared using DTM Consulting's Geotools shareware program, which functions as an extension in ESRI's ArcView software.)

trends correspond to minor surface-fault trends only in northwestern Louisiana (in areas 1 and 2 of his figure 3). Two of the three trends, N-S and N80°–90°W, correspond to the strikes of two of three joint sets recently reported by Washington and Strickland (2000) as controlling drainage lineaments in north Louisiana, and the main N-S trend also corresponds to the main trend of the drainage lineaments interpreted at 1:500,000 scale in north Louisiana by McCulloh (1995, his figure 4). A N-S trend was also previously documented in sets of stream-course orientation data by Barton (1933) in south Texas, and by Melton (1959) in central Oklahoma. Barton attributed it, along with NW-SE and NE-SW maxima, to fractures corresponding to underlying basement trends; whereas Melton hypothesized it as an effect of differential insolation of soil in valley heads opening generally southward. A N-S maximum has also been reported for other datasets of different kinds interpreted by Gay (1973) as caused by basement structure. As Figures 2 and 3 show, there is at least some basis for considering a N-S trend as possibly attributable to systematic fracturing in the Louisiana Gulf Coast.

The above trends, however, are visually identifiable peaks on the rose diagram, which depicts counts in 10° class bins. Following the procedures outlined by Davis (1986, p. 316, 325-326) gives a mean orientation of N17.5°W ± 4.2° with 95 percent probability for the entire population of orientations measured for 100-m segments. An application of procedures described by Davis (1986, p. 314-326) to test a null hypothesis of circular uniformity of this population assuming a von Mises distribution indicated that the population deviates significantly from random ($\overline{R}$=0.035; κ≈0.07004; $2n\overline{R}^2 = 697.323$, $\alpha<<0.001$; cf. Davis 1986, Tables 5.6, 5.7; Mardia 1972, Appendix 2.5).[4]

If the seemingly clear rectilinearity manifested in portions of the Louisiana stream net does in fact reflect some controlling geological influence(s), and if the most likely influence is that of fracturing, then the lack of a clear correspondence between the net's prominent orientation frequencies and the strikes of mapped faults suggests control by abundant but cryptic, as-yet unmapped faults, control by joints, or both. If the existing mapped faults can be considered at least representative, then to the extent that lineaments reflect structure rather than a south-southeasterly regional drainage gradient, the likelihood of control of the principal orientation frequencies of the stream net by cryptic joint systems is increased. Joints are most probably cryptic owing to the comparatively thick overburden of Quaternary sediment, the poor consolidation of most Tertiary strata, and the

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4. A test of the distribution depicted in the rose diagram assuming a chi square distribution produces results strongly rejecting circular uniformity, $\chi^2(17, N = 289{,}356) = 3670.24$, $p < 0.0001$; but the test is more subject to a documented problem associated with significance testing of very large samples, viz, that such large sample sizes in and of themselves result in smaller p values than would be the case with smaller samples (Johnson 1999; Daniel 1998). The test for randomness assuming the von Mises distribution, as outlined by Davis (1986, p. 321-325), is more sensitive with large samples.

weathering effects of the humid subtropical climate.

The stream-net data used and other map information examined herein permit no conclusive statement regarding the ultimate origin of the structures inferred from them. One possibility is that they could reflect a Quaternary stress regime, including a stress regime initiated at an earlier time that continued up to the present. Stauffer and Gendzwill (1987) interpreted NW- and NE-striking joints of the North American midcontinent stress province as contemporaneously produced, by vertical uplift in conjunction with the midcontinent stress field attributed to westward movement of the North American plate. Production of joints responsible for NW- and NE-trending drainage lineaments in Louisiana by this mechanism would require influence over large parts of the state at times by the midcontinent stress field. Another possibility is that the inferred structures could, as favored by Gay (1973), represent propagation in young sediment of a pattern in underlying older strata: the pattern of lineaments and fractures in Figures 2 and 3 replicates his "basement fault block pattern" (Gay n.d.). This latter possibility of propagation from depth is suggested at least in south Louisiana because the reactivated growth faults that have surface expression there probably reflect the current stress field and recent effects of depositional loading (Nunn 1985). Escarpments probably representing the fault-line scarps of such faults are much more abundantly documented now than previously (Heinrich 1997, 2000). These faults are arrayed with an arcuate pattern of strikes (ENE in western south Louisiana through WNW in eastern south Louisiana) consistent with depositional loading, which is uncharacteristic of the predominant orientations of the drainage lineaments examined here. If the fracture sets inferred from rectilinear drainage patterns are propagated from deeper structures that predate the earliest period of growth faulting, the deeper structures must predate the early Tertiary. A basement pattern with NW- and NE-trending elements in west-central Louisiana was postulated by Smith (1984), who continued a line of research begun by Zeosky (1982); he modeled basement topography from gravity and magnetic data, which he concluded show basement horst-and-graben structures delineated by lineations similar to the lineaments of Fisk (1944).

Regardless of their origin and age, fractures inferred from the stream net could measurably influence surface and subsurface processes that depend substantially on permeability. Documentation or plausible inference, however indirect, of the influence of systematic fractures on the stream net in a number of areas thus could have implications for potentially understanding discrepancies between measured and modeled groundwater flow. In areas where they seem unaccountably large and/or intractable, the geologic and hydrographic setting may be examined to see whether fracturing might account for the discrepancies.

For example, in the Martinville area northwest of Covington, Louisiana, Winston (1997) encountered potentiometric anomalies that he suspected were due to fractures, though he had no independently acquired data on fracturing. Examination of a draft surface-geologic overlay of the 7.5-minute quadrangle encompassing the area (Figure 7) showed clear rectilinearity of its alluvial bottoms in places. But the area also contains a 3-m (10-ft) south-facing escarpment analogous to those comprising the fault-line scarps of reactivated growth faults in south Louisiana. The best known of these, the faults of the Baton Rouge system, have their northernmost extent some 10 to 16 kilometers (6 to 10 miles) to the south of the escarpment traced in the Martinville quadrangle, and show strikes concordant with it. So even if fractures could be documented in a core, it would be necessary (depending on proximity to the escarpment) to know their orientations to distinguish between the two possible types. It seems noteworthy in any case that both the WNW-trending escarpment and the NW- and NE-trending drainage lineaments are here seen together, because Saucier (1974, 1994) implied mutual exclusivity of such features, and cited the known faults of the Baton Rouge system in southeastern Louisiana in conjunction with his discounting of the differently characterized drainage lineaments mapped by Fisk (1944). The conjunction here,

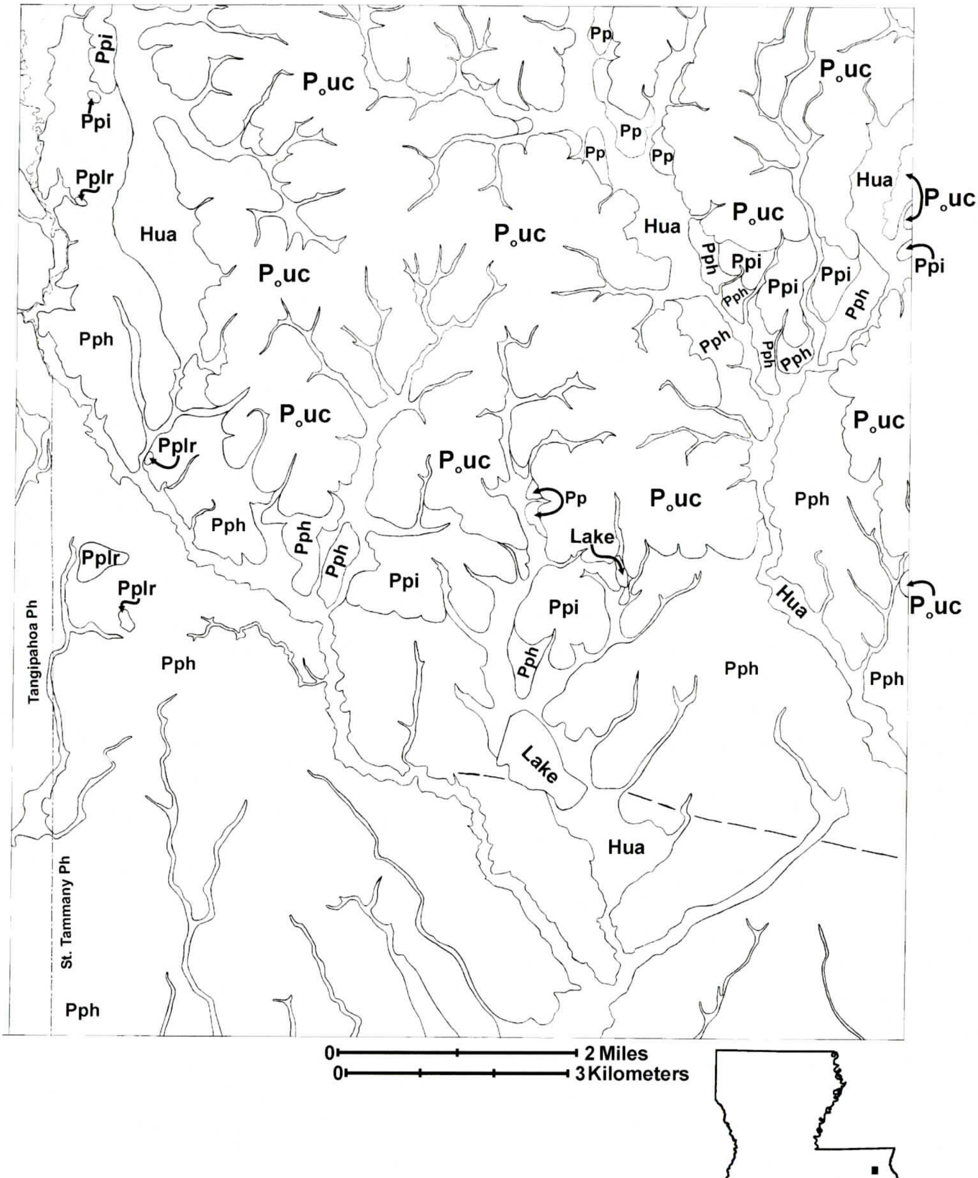

Figure 7. Surface geology of the Martinville 7.5-minute quadrangle, southeastern Louisiana. Alluvial bottoms showing rectilinear patterns of NW- and NE-trending drainage lineaments occur together with a 3-m (10-ft) south-facing, WNW-trending escarpment concordant with the fault-line scarps of reactivated growth faults of the Baton Rouge system to the south. $P_o$uc = Pliocene Upland allogroup, Citronelle Formation; Ppi = Pleistocene Prairie Allogroup, Early Sangamon, Irene alloformation; Pph = Pleistocene Prairie Allogroup, Late Sangamon, Hammond alloformation; Pp = Pleistocene Prairie Allogroup, undifferentiated; Pplr = relict Pleistocene ridges comprising sand hills on the surface of the Hammond alloformation; Hua = Holocene undifferentiated alluvium; dashed line = escarpment. Geologic mapping by the author, of one of 32 source maps recompiled in 1:100,000-scale quadrangle format by McCulloh and others (1997).

and in the Baton Rouge area (Birdseye and others 1988), of growth faults with such lineaments, again suggests that propagation of a preexisting pattern from depth could plausibly account for the lineaments at least in south Louisiana.

For the present the influence of fracturing on groundwater flow remains speculative, but in light of the emphasis commonly given to fracturing as a source of secondary permeability in the context of petroleum exploration it is an important consideration. Additionally, given that pedogenic fractures formed by cyclic desiccation and rehydration are inferred by Hanor (1993, 1995) to have significantly enhanced permeability in fine-grained surficial and near-surface coastal-plain sediment, it seems reasonable to consider that systematic fractures of tectonic origin are also candidates for increasing permeability and influencing groundwater hydrology in similar semiconsolidated sediment. If fractures can be adequately documented in association with interpreted drainage lineaments at more than a few individual sites, an important question to address will be whether the lineaments correspond to zones of increased fracture density—"fracture traces" of Lattman (1958), or "joint-swarm corridors" of Bevan and Hancock (1986, p. 359)—and if so, the degree of corresponding localization of any hydrological influence.

New data and techniques will undoubtedly enhance both the perception and analysis of indirect indicators of surface structure, and facilitate their eventual use as a proxy for structure. The rectilinear patterns discussed herein do not stand out necessarily on standard topographic quadrangle maps because of the busyness of the totality of base information on such maps in combination with the low to moderate relief in most parts of the state. Until very recently in the author's experience, perception of this aspect of Louisiana's surface geology generally required having or preparing a map of the alluvium at a sufficiently large scale for a given area. The advent of recently available digital datasets and techniques, however, makes possible the perception of rectilinear drainage characteristics more directly and with higher resolution in places. An example of this is shown in Figure 8, a view of a digital elevation model (DEM) of LIDAR ("LIght Detection And Ranging") data for the northwestern quarter of the Wilmer quadrangle geologic map shown in Figure 2. The DEM depicts a terrane that appears systematically jointed, in places strikingly so, and shows with greater clarity some of the trends apparent on the geologic map.

As better data sets become available, it will be worthwhile to repeat the present exercise using them; to use the approach at larger scales for smaller study areas; and to evaluate any trends in relation to an estimation made with acceptable precision of the direction of the regional drainage gradient (which the author was unable to obtain for inclusion here). One data set soon to become available that would represent a substantial increase in quality over that used herein is the 1:24,000-scale stream-net layer of the U.S. Geological Survey's newly compiled National Hydrography Dataset. Summarizing stream-segment orientation frequencies in smaller areas, especially for individual drainage basins and areally restricted geologic terranes, should permit more meaningful correlation of any prominent trends with hypothesized geologic controls based on detailed knowledge of their geology. Additionally, strain measurements for the state will likely become publicly available in the coming years (e.g., via the Louisiana Center for Geoinformatics); such measurements should permit evaluation of the degree to which systematic fracture sets inferred from proxies such as the stream net reflect the current stress regime.

CONCLUSIONS

A preliminary summary of frequencies of stream-course orientations in Louisiana shows their essential nonrandom distribution. On a rose diagram with 10° classes, the strongest trend visible is oriented essentially N-S, a somewhat weaker trend is oriented N20°–30°W, and a much weaker trend is oriented N80°–90°W. The mean direction of the entire population of orientations is N17.5°W ± 4.2° at the 95-percent probability level. Correspon-

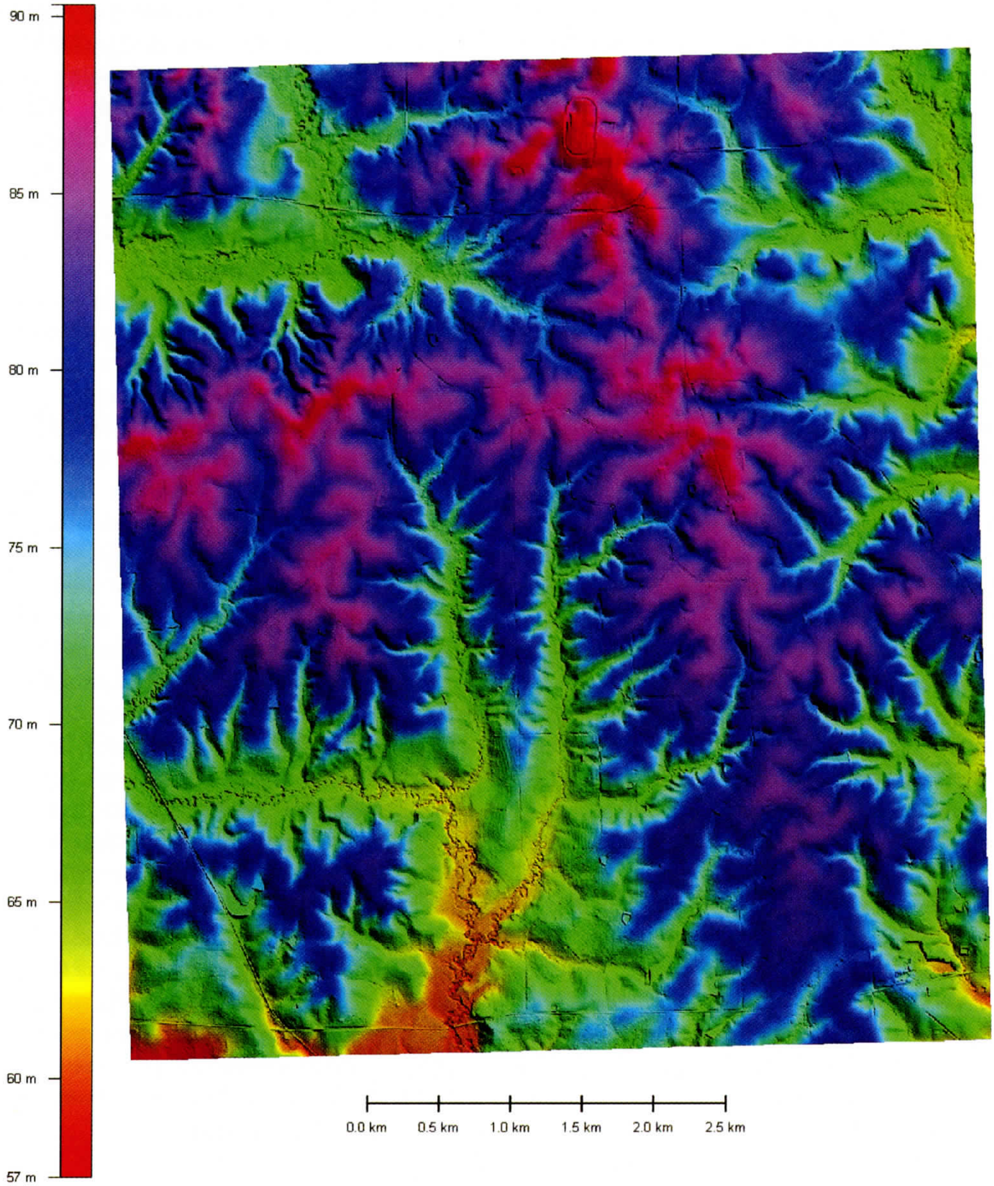

Figure 8. Colored shaded-relief view of digital elevation model of LIDAR ("LIght Detection And Ranging") data for the northwestern quarter of the Wilmer quadrangle shown in Figure 2: downloaded from Atlas website (http://atlas.lsu.edu) and viewed with Global Mapper DEM viewer. Source: Louisiana Federal Emergency Management Agency (FEMA), and U.S. Army Corps of Engineers, St. Louis District.

dence of these trends with the strikes of independently mapped surface and subsurface faults is weak. For drainage patterns that are affected by some geological control as well as by a south-southeasterly regional drainage gradient, this suggests joints as the probable influence. The joints have likely remained cryptic because of the comparatively great extent and thickness of geologically young strata consisting of unconsolidated and poorly consolidated Cenozoic, predominantly Quaternary sediment, together with effects of humid-subtropical weathering. The inferred structures could reflect either a Quaternary stress regime or a preexisting pattern recently inherited in young sediment; available data do not yet compel either interpretation. In south Louisiana at least, because the traces of reactivated growth faults that probably reflect the current stress field are in places juxtaposed with differently oriented drainage lineaments, propagation of a preexisting fracture pattern from depth appears plausible. The fractures inferred as responsible for drainage lineaments have potential significance for surface and subsurface processes that depend substantially on permeability, such as groundwater flow.

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CONTACT AUREOLE OF THE ROLESVILLE BATHOLITH, EASTERN NORTH CAROLINA PIEDMONT: PETROLOGY AND IMPLICATIONS

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ABSTRACT

Intrusion of plutons of the late Paleozoic Rolesville batholith imposed a thermal metamorphic imprint on greenschist facies phyllites and metavolcanic rocks within the Spring Hope terrane, producing porphyroblasts of garnet, andalusite, and staurolite in metapelitic rocks, and widespread hornfelsic textures. Mafic rocks developed assemblages of hornblende + garnet + plagioclase, and locally, garnet + clinopyroxene + Ca-plagioclase + zoisite/clinozoisite. Porphyroblasts are syn- to post-deformational with respect to matrix fabrics. Mineral analyses from key assemblages in the contact zone reflect rock composition (pelitic or mafic) and metamorphic conditions within the hornblende hornfels and low-pressure (andalusite - sillimanite) amphibolite facies. Thermobarometric calculations yield P-T estimates of 540° to 618°C and 1.6 to 3.6 kbar adjacent to the Archers Lodge and Bunn granitoid plutons.

When combined with previous studies, these results suggest the possibility that over 10 km of crust may have been removed along the western side of the batholith. This is in agreement with gravity models of the eastern Piedmont that interpret the batholith to be an eastward-dipping granitoid body. Vertical throw along the Mesozoic Jonesboro normal fault can account for no more than a few km of the inferred uplift. The remainder may be attributable to hypothetical vertical motion along an unknown fault or faults. Alternatively, the apparent crustal tilting may be explained by regional folding during or after the intrusion of the batholith, or by a combination of folding and faulting.

INTRODUCTION

The Carboniferous Rolesville batholith, located in the eastern Piedmont of North Carolina, is the largest intrusive body in the southern Appalachians (Speer, 1994a). The Rolesville batholith is composite (Farrar, 1985a; Speer, 1994a) and part of a larger group of plutons emplaced during the Late Paleozoic Alleghanian orogeny. The contact aureole present in country rocks south and east of the batholith has not previously been studied or described in the literature. The primary goals of this paper are to characterize petrologically the thermal metamorphic imprint imposed on the country rocks, and to estimate the depth of emplacement of two plutons in the batholith.

In the Piedmont and Carolina zones, the Alleghanian orogeny included a distinct phase of plutonism, as well as regional metamorphism and development of extensive ductile shear zones (Russell and others, 1985; Secor and others, 1986; Horton and others, 1987). Carboniferous-Permian magmatism resulted in the emplacement of numerous granitoid and sparse gabbroic plutons (Figure 1; Fullagar, 1971; Fullagar and Butler, 1979).

Regional Geologic Setting

The southern Appalachian orogen may be divided into four first-order tectonostratigraphic subdivisions: the Cumberland zone, Piedmont

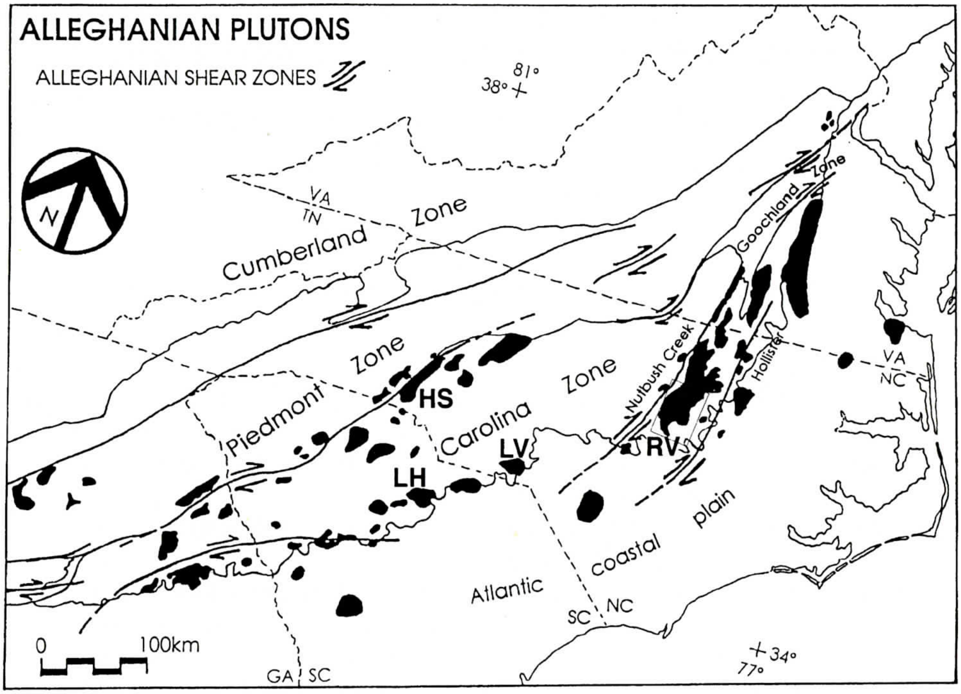


Figure 1. Alleghanian plutons of the southern Appalachian orogen (in black). Plutons are spatially and temporally related to Alleghanian ductile shear zones (e.g. Nutbush Creek; Hollister). After Horton and others (1989); Speer and others (1994b); Hibbard and Samson (1995); and Coler and others (1997). RV = Rolesville batholith; HS = High Shoals pluton; LV = Lilesville pluton; LH = Liberty Hill pluton.

zone, Carolina zone, and Goochland zone ((Figure 1; Hibbard and Samson, 1995). Each zone consists of rocks possessing similar gross characteristics, such as overall ages and affinities. This study is concerned with Late Proterozoic to Cambrian metavolcanic and metaplutonic rocks of peri-Gondwanan origin belonging to the Carolina zone. The zones may be subdivided into tectonostratigraphic terranes (Horton and others, 1989, 1994). Terranes most important to this study are the Spring Hope and the Raleigh terranes.

The northern and western margins of the Rolesville batholith intrude the Raleigh terrane; the southern and eastern intrude the Spring Hope terrane (Figure 2). The batholith is located just east of the Nutbush Creek fault, and at the southern end of the Lake Gordon mylonite zone. Both shear zones are Alleghanian ductile faults with documented dextral motion (Druhan and others, 1988, 1994; Horton and others, 1993). The Macon mylonite zone, another probable Alleghanian fault (Sacks, 1999; Farrar, 1985a), appears to terminate just north of the Castalia pluton. The Carolina and Crabtree terranes, located west of the batholith and separated from it by the Nutbush Creek fault (Figure 2), are inferred to represent portions of one or more ancient volcanic arcs of similar age to the Spring Hope terrane. The Leesville fault separates the Carolina terrane from the Crabtree terrane (Blake and others, 2001). Also located to the west is the Triassic Deep River basin, bounded along its eastern margin by the Jonesboro normal fault.

The Raleigh terrane consists predominantly of mafic and felsic orthogneisses metamorphosed to mid- to upper-amphibolite facies

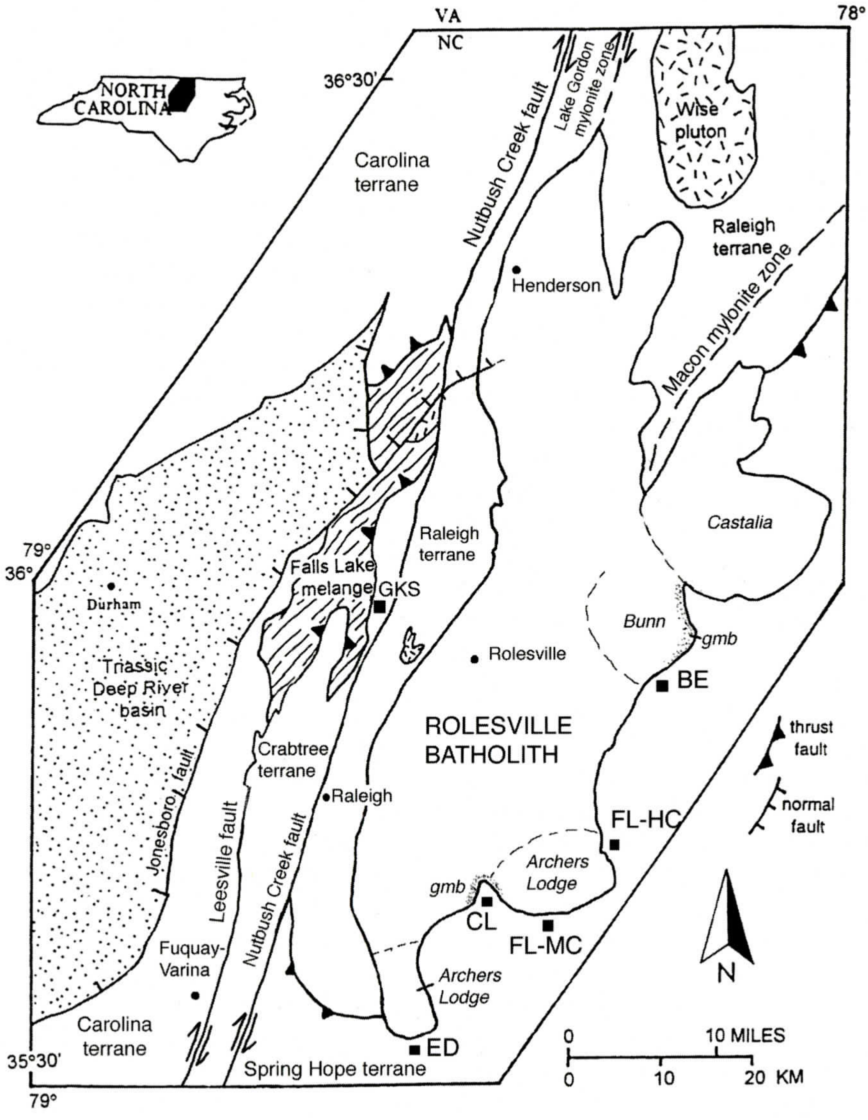


Figure 2. Simplified geologic/tectonic map of the eastern North Carolina Piedmont (after Stoddard and others, 1991; Horton and others, 1994; Speer, 1994a). Sample location areas: BE = Bunn; FL-HC = Hocutts Crossroads; FL-MC = Mill Creek; CL = Clayton; ED = Edmondson. GKS is garnet-kyanite schist locality of the Crabtree terrane referred to in the text. Locally developed garnet-muscovite-biotite granitoid border facies (Speer, 1994a) is indicated by *gmb*. Coastal Plain overlap is omitted for clarity.

(Parker, 1979; Farrar, 1985a; Stoddard and others, 1991; Heller, 1996; Blake and others, 2001). A preliminary $^{207}Pb/^{206}Pb$ zircon age of 544 Ma was reported for hornblende gneiss (Raleigh gneiss) within this terrane (Horton and Stern, 1994). The Spring Hope terrane consists primarily of greenschist facies phyllite and metavolcanic rocks and is interpreted to represent an ancient volcanic island arc (Farrar, 1985b; Horton and others, 1989; Stoddard and others, 1991). Horton and Stern (1994) reported a preliminary $^{207}Pb/^{206}Pb$ zircon age of 544 Ma for a felsic metatuff within the Spring Hope terrane, and Goldberg (1994) reported a preliminary $^{207}Pb/^{206}Pb$ zircon age of 590 Ma from a separate felsic volcanic unit. Some studies suggest that rocks of the Raleigh terrane (and perhaps the Crabtree terrane) may represent, at least in part, a higher grade, deeper crustal level equivalent of rocks of the Spring Hope terrane (Samson and others, 1995; Heller, 1996; Stoddard and others, 1996).

The boundary between the Raleigh and Spring Hope terranes in this area has been mapped as a decollement style thrust fault of probable pre-Alleghanian age (Farrar, 1985b). The nature and location of this fault are a matter of debate, as some authors (Carpenter and others, 1998a,b) show this boundary, and a portion of the Raleigh terrane, extending around the eastern and southern margins of the Rolesville batholith. Other interpretations suggest that only the Spring Hope terrane crops out southeast of the batholith, and that the granite (Horton and others, 1989, 1994), truncates the thrust fault.

This study focuses on rocks southeast of the Bunn and Archers Lodge plutons, and supports the interpretation that these rocks belong to the Spring Hope terrane, not the Raleigh terrane. The argument is as follows. Where the Raleigh terrane is well characterized, it consists of intermediate to mafic gneisses interpreted to have igneous protoliths, and it contains no metapelitic schist (Horton and others, 1994). The Spring Hope terrane, however, has been interpreted to be derived from both volcanic and pelitic sedimentary protoliths (Farrar, 1985a). Compared to the greenschist-grade rocks in the main part of the Spring Hope terrane, the rocks of the study area have pelitic and volcanic protoliths, but show a higher metamorphic grade. The difference in grade is attributed to thermal metamorphism from intrusion of the Rolesville batholith, whose contact aureole follows the batholith margin along the south and east sides. In the "type area" of the Raleigh terrane, west of the batholith, a contact aureole is absent, likely because rocks of the Raleigh terrane were deeper and at a temperature similar to that of the intruding granitoid magma. Evidence of contact metamorphism in rocks of the Spring Hope terrane is the focus of this study.

Alleghanian Magmatism

The Alleghanian magmatic event produced approximately 60 plutons (totaling over 10,500 km^2) in the Carolina zone and under the cover of the coastal plain, from Georgia to Virginia (Figure 1; Speer and others, 1994b). These plutons range in age from 335 to 263 Ma (Fullagar, 1971; Fullagar and Butler, 1979; Speer and others, 1994b). The plutons are spatially and temporally associated with regional-scale Alleghanian dextral shear zones, that may have provided a locus for their ascent and emplacement. The shear zones may imply the mechanism of magma generation (Speer and others, 1980; 1994a,b). The Rolesville batholith is the largest of the Alleghanian plutons (>2000 km^2) and is a composite body.

Previous Studies

Studies on the contact zones of the Alleghanian Lilesville and Liberty Hill plutons (see Figure 1) documented their contact aureoles (Evans and Speer, 1984; Speer, 1981). About 12 km east of the Rolesville batholith, the Sims pluton intrudes metasedimentary rocks of the Spring Hope terrane and has a weakly developed contact aureole (Farrar, 1985a; Speer, 1997).

Farrar (1985a) mapped a large portion of the eastern Piedmont of North Carolina, and described the Rolesville batholith as consisting of three texturally distinct "facies:" the Rolesville main facies, the Archers Lodge porphyritic facies, and the Louisburg facies. In that study and earlier work, the Castalia pluton (Figure 2) was mapped as a separate granitic body, located adjacent to the Rolesville batholith. In a subsequent study, Speer (1994a) included the Castalia pluton as a part of the Rolesville batholith. He (Speer, 1994a) distinguished approximately 15 different granitoid types, each exemplified by a separate plutonic body. Two plutons and an additional granitoid type, described and named by Speer (1994a) are encountered in the study area: the Bunn granitoid in the Bunn East quadrangle, the Archers Lodge megacrystic granite in the Flowers, Clayton and

Table 1. Inferred equilibrium mineral assemblages and mineral abbreviations. Minerals pseudomorphically replaced are listed in *italics*. Relict minerals present but excluded from the assemblage are in parentheses. Common retrograde chlorite and fine-grained white mica are not listed. Bunn mafic rock is from Stoddard (1992).

Pelitic and semipelitic rocks (all contain ms + qtz in addition)

Bunn	grt + st + bt + ilm ± pl grt + st + bt + ilm + and ± pl
Edmondson	and + st + grt + bt + pl + ilm
Clayton	grt + bt + pl + ilm grt + bt + pl + ilm + *and* grt + bt + pl + ilm + st grt + bt + pl + ilm + st + *and* pl + ilm
Mill Creek	grt + pl + ilm + mag + *and* grt + pl + ilm + mag + *and* + bt grt + pl + ilm + mag + *and* + fib grt + pl + ilm + mag + *and* + bt + fib grt + bt + pl + ilm + mag (cld) grt + bt + pl + ilm + mag + *and* (cld) grt + fib + pl + ilm ± ep ± bt and + fib + pl + ilm + mag
Hocutts Crossroads	fib + bt + mag + tur + pl fib + bt + mag + tur + pl + grt

Mafic rocks

Bunn	hbl + pl + qtz + grt + ep/czs + ttn + ilm + mag ± bt
Clayton	grt + qtz + pl + ttn + zo grt + qtz + pl + ttn + zo + cpx grt + hbl + qtz + pl + ttn
Mill Creek	hbl + ged + grt + pl + ilm + qtz

Mineral abbreviations (modified from Kretz, 1983)

act	actinolite	fib	fibrolitic sillimanite	phl	phlogopite
alm	almandine	grt	garnet	pl	plagioclase
and	andalusite	ged	gedrite	prp	pyrope
ann	annite	grs	grossular	qtz	quartz
an	anorthite	hd	hedenbergite	ser	sericitic white mica
bt	biotite	hbl	hornblende	sid	siderophyllite
cpx	Ca-clinopyroxene	ilm	ilmenite	sil	prismatic sillimanite
chl	chlorite	kfs	K-feldspar	sps	spessartine
cld	chloritoid	ky	kyanite	st	staurolite
crd	cordierite	mag	magnetite	ttn	titanite
czs	clinozoisite	ms	muscovite	tur	tourmaline
di	diopside	opq	unidentified opaque mineral	ts	tschermakite
ep	epidote	opx	orthopyroxene	zo	zoisite

Edmondson quadrangles, and an unnamed garnet-muscovite-biotite border facies granitoid (gmb) in the Clayton and Bunn East quadrangles (Figure 2).

Published geochronological work on the Rolesville batholith is sparse. Preliminary $^{207}Pb/^{206}Pb$ zircon ages of 312 and 298 Ma were reported for two granitoid phases of the Rolesville batholith by Horton and Stern (1994). Recently, more precise $^{207}Pb/^{206}Pb$ zircon ages of 297.6 ± 3.2 Ma (upper intercept) and 298.8 ± 4.3 Ma (concordant) were reported by Schneider and Samson (2001) for the Rolesville main phase and Louisburg phase.

Methods

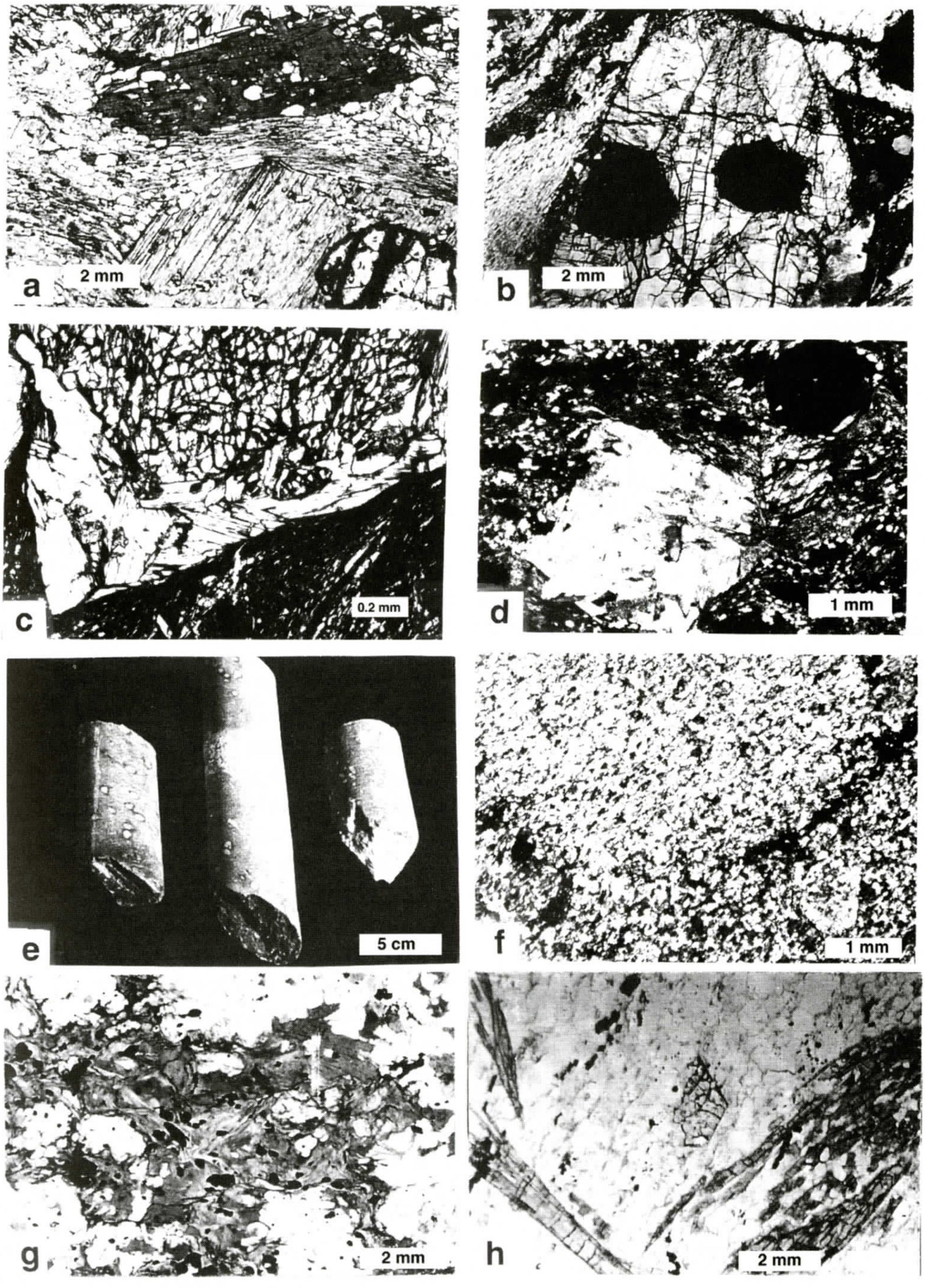
Approximately 100 hand samples were collected from locations around the Rolesville batholith based on: (1) proximity to the batholith, (2) rock type (particularly rocks with pelitic sedimentary or mafic igneous protoliths), and (3) outcrop/exposure of fresh, unweathered samples. Drill core samples from a location in the Edmondson quadrangle (Figure 2) were also obtained for study. Thin sections from 60 samples were analyzed using the petrographic microscope in order to determine mineral assemblages and microscale metamorphic textures.

Polished thin sections were prepared for electron microprobe analysis from 20 rock samples containing mineral assemblages appropriate for thermobarometry (primarily grt + bt ± and ± sil or grt + hbl; mineral abbreviations used are listed in Table 1). Additional minerals were analyzed from selected samples to better characterize rock types and metamorphism. Individual analyses are presented in Gaughan (1999).

All mineral analyses were performed on an automated ARL-SEMQ six spectrometer electron microprobe in the Department of Marine, Earth and Atmospheric Sciences at North Carolina State University, using an accelerating voltage of 15 kV, sample current of 0.015 ΓA, and 10-second counting time, with a beam diameter of about one micron. Raw data were corrected using the phi-rho-Z method (Philibert, 1963, in Heinrich, 1981). Mineral reference standards of garnet, hornblende, ilmenite, plagioclase, anorthoclase, microcline, and a synthetic Mn-olivine were provided by the Smithsonian Institution.

Between five and ten spot analyses on a single grain were averaged for each mineral analysis. Typically, minerals that displayed zoning were divided into core and rim regions that were analyzed separately. In thin sections to be used for thermobarometry, domains were selected in which the appropriate minerals (grt-bt-pl; grt-hbl-pl) were in mutual contact or separated by

Figure 3. Selected petrographic features of metamorphic rocks discussed in text. Color versions may be viewed at <http://www4.ncsu.edu/eos/users/s/stoddard/public/Figure3.jpg>.
a. Biotite and garnet porphyroblasts in sample ABE-5. Biotite contains inclusions aligned parallel to the foliation. Biotite also encloses earlier garnet grain at the lower right. Plane-polarized light.
b. Two garnets enclosed within staurolite porphyroblast in sample BEA-4. Crossed polars.
c. Andalusite porphyroblast in sample BEA-5. Although marginally replaced by white mica, the original euhedral outline is clear. Plane-polarized light.
d. Pseudomorph of white mica after andalusite in sample ABE-5+. Garnet, at extinction, in upper right, and staurolite between garnet and andalusite. Crossed polars.
e. Photograph of drill core samples from the Edmondson area. Porphyroblasts of andalusite, light colored with dark biotite rims, are visible. Width is 30 cm.
f. Poikiloblast of andalusite in sample ED 3-26. Andalusite occupies the upper two-thirds of the photo. A portion of its outline is defined by a dark biotite rim. Lower portion of photo shows hornfelsic texture of the matrix, and in addition to biotite, this view contains staurolite porphyroblasts. Crossed polars.
g. Mats of fibrolitic sillimanite intergrown with biotite in sample FLA-(HC)-4+. Abundant opaque grains are magnetite. Plane-polarized light.
h. Hornblende, gedrite, and garnet in sample FL-(MC)-14. Hornblende (right) is green and typically occurs in aggregates; orthoamphibole (left) is light gray and bladed. Plane-polarized light.


a
2 mm
b
2 mm
c
0.2 mm
d
1 mm
e
5 cm
f
1 mm
g
2 mm
h
2 mm

only one or two grains of other minerals, and in apparent textural equilibrium.

The mineral analyses were recalculated into structural formulas using a simple computer spreadsheet and the computer program Hyperform (DeBjerg and others, 1992). For garnet, pyroxene, and opaque oxide mineral analyses, ferric iron content was estimated by assuming electroneutrality and adjusting the Fe^{2+}/Fe^{3+} ratio accordingly. For biotite and amphibole, all Fe was assumed to be Fe^{2+} to minimize estimated site vacancies.

ROCK DESCRIPTIONS

Late Proterozoic to early Paleozoic rock units are exposed adjacent to the Late Paleozoic Rolesville batholith within the Bunn East, Edmondson, Clayton and Flowers 7.5-minute quadrangles (Figure 2). During the 1990s, the geology of these areas was mapped at the 1:24,000 scale by the North Carolina Geological Survey (NCGS) and its contractors (e.g. Stoddard, 1992; Carpenter and others, 1995, 1998a,b). Metamorphic rocks within the study area are divided into metapelitic, mafic, and felsic metavolcanic types. The emphasis for this study is on the metapelitic and metamafic rocks because of their sensitivity to changes in metamorphic grade. Locally, in the vicinity of the Rolesville batholith, samples have metamorphic textures and minerals that overprint an earlier regional metamorphic fabric.

Below, petrographic descriptions of each lithologic type encountered within the study area are provided, with the primary focus being on metamorphic overprinting adjacent to the Rolesville batholith. Emphasis is placed on description of mineral assemblages and textures used in discerning the metamorphic history and pressure-temperature conditions experienced by these rocks. Mineral assemblages are listed in Table 1, as are the mineral abbreviations used throughout this paper.

Metapelitic Rocks

Metapelitic rocks were studied from five sample areas referred to as: Bunn, Edmondson, Clayton, Mill Creek and Hocutts Crossroads (Figure 2). The samples come from several different map units, but most have developed similar mineral assemblages adjacent to the plutons. Further details may be found in Gaughan (1999).

Bunn

Metapelitic rocks within the Bunn area were collected from Crooked Creek and smaller tributaries of the Tar River. Stoddard (1992) mapped these rocks and noted that near the contact with the Bunn granitoid, porphyroblasts of garnet, staurolite and andalusite occur in schist. These minerals are absent in the compositionally similar lower grade rocks away from the pluton.

The pelitic schists in this area are typically porphyroblastic rocks that contain prominent euhedral porphyroblasts of staurolite, smaller garnet, and sparse andalusite. Biotite poikiloblasts contain inclusions of white mica, quartz, and opaque minerals aligned roughly parallel to the matrix schistosity (Figure 3a).

Staurolite occurs in abundant clusters of coarse poikiloblastic grains up to 5 mm across that are typically euhedral to subhedral in shape, but are locally skeletal grains. Common euhedral grains with inclusion-free cores, and outer zones with local, rounded inclusions of quartz, suggest multiple stages of staurolite growth (or changing rates of growth).

Garnet porphyroblasts are typically subhedral or rounded, and in many samples are altered to red-brown iron oxide(s). Many garnets are completely contained within biotite (Figure 3a) or staurolite (Figure 3b). Several samples contain 5-12 mm long prisms of andalusite (Figure 3c), showing varying degrees of replacement by coarse white mica (Figure 3d).

Edmondson

Samples were obtained from four drill cores from a location approximately six km ESE of the community of Edmondson, and two km north of Coats Crossroads, along Beaverdam Creek. This area lies within an argillite unit of the Spring Hope terrane mapped by Carpenter and others (1995). Core samples were taken from depths ranging from 8 to 99 meters.

The presence of white andalusite poikiloblasts makes the rocks "spotted hornfelses" (Figure 3e, 3f). Large andalusite grains are surrounded by dark reaction haloes of biotite, and also contains biotite inclusions that preserve the matrix foliation. Andalusite is replaced and pseudomorphed by fine-grained white mica in some samples.

Smaller porphyroblasts consist of staurolite and garnet. Staurolite poikiloblasts are subhedral to euhedral and contain abundant inclusions of quartz and minor ilmenite (Figure 3f). Narrow veins of unoriented quartz cut through several samples, and in one sample, abundant staurolite grains surround one such vein, suggesting that fluid influx facilitated mineral growth. Sparse garnet porphyroblasts are typically small, rounded, anhedral grains with minor inclusions of quartz and biotite. Opaque minerals in this rock are predominantly ilmenite and minor sulfide minerals occurring as rounded irregular grains.

Clayton

Metapelitic samples were collected from the garnet-muscovite-biotite schist unit of Carpenter and others (1998b), adjacent to the Clayton reentrant (Speer, 1994a). The rocks are schists, often containing small porphyroblasts of garnet and poikiloblasts of staurolite. Ovoid "porphyroblasts" composed of fine-grained sericitic aggregates and less abundant coarse unoriented flakes of white mica are inferred to be pseudomorphs after andalusite. Most of the garnet cores contain curved inclusion trails of quartz and opaque minerals that are aligned oblique to the foliation of the matrix. Inclusion trails of quartz in staurolite are aligned oblique to the matrix foliation, and some staurolite grains have quartz pressure shadows. Some staurolite grains partly enclose garnet porphyroblasts, and in one sample, euhedral staurolite crystals are enclosed by biotite. Many staurolite porphyroblasts are partially replaced by combinations of quartz, white mica, biotite, and chlorite.

Mill Creek

Samples were collected from Mill Creek, a tributary of the Neuse River, at the western edge of the Flowers quadrangle; Carpenter and others (1998a) included these rocks in their garnet-muscovite-biotite schist and biotite-muscovite-quartz-feldspar gneiss units. Samples from this area have textures and assemblages similar to the Clayton metapelitic rocks and are thought to belong to the same unit.

The schists from this area contain porphyroblasts of garnet and nearly oval aggregates of fine-grained white mica after andalusite, and exhibit a well-developed schistosity. Garnet porphyroblasts are subhedral or rounded and relatively inclusion free. Cores of some grains, however, contain abundant inclusions of quartz, suggesting two phases of garnet growth (or possibly changing growth rates). A distinct garnet overgrowth texture occurs in one sample, along with concentrations of small, euhedral garnet grains. A few samples contain garnets with curved inclusion trails of quartz. Andalusite porphyroblasts in several samples are largely to entirely replaced by aggregates of coarse- or fine-grained white mica, or by fibrolitic sillimanite. A few samples contain garnet and chlorite aggregates that may be pseudomorphs after euhedral staurolite porphyroblasts. Some samples contain minor amounts of light green-blue chloritoid, replaced on its edges by white mica, quartz, and chlorite. Tiny epidote grains with less abundant muscovite and chlorite, apparently replacing a former Ca-bearing mineral, occur in one sample.

Hocutts Crossroads

Rocks mapped as amphibolite facies heterogeneous gneiss and schist by Carpenter and others (1998a) occur in the Flowers quadrangle in tributaries of the Little River. Carpenter and others (1998a) associate this unit with the Raleigh terrane, whereas Horton and others (1989, 1994) include the rocks of this area as part of the Spring Hope terrane.

The rocks are massive hornfels with no visible foliation. Fibers of sillimanite are found throughout all samples. Commonly, sillimanite is granular or nearly prismatic. There are also some dense mats of tan fibrous sillimanite intergrown with less abundant biotite, white mica, and quartz (Figure 3g). Abundant, euhedral to anhedral magnetite grains are scattered throughout all samples along with minor amounts of anhedral, deep blue-green, pleochroic tourmaline. Sparse anhedral garnet porphyroblasts are up to one mm in diameter, and are highly poikiloblastic (spongy or skeletal), with inclusions of quartz. Several samples contain aggregates of fibrous sillimanite, white mica, and quartz that appear to be pseudomorphs after an earlier, rounded porphyroblast mineral.

Metavolcanic Rocks

Metavolcanic rocks found in the Bunn, Mill Creek, and Clayton areas are inferred to have primarily mafic volcanic protoliths. Bunn samples, collected and described previously during mapping by Stoddard (1992), also include felsic to intermediate metavolcanic rocks.

Metavolcanic rocks from the Bunn East quadrangle (Stoddard, 1992) were reexamined in this study. Felsic to intermediate metavolcanic rocks from the Bunn area typically consist of a fine-granoblastic matrix of quartz, plagioclase, epidote, and titanite, with traces of magnetite and ilmenite, and larger grains of amphibole and garnet. Abundant elongate to acicular poikiloblastic hornblende defines a moderate foliation. Garnets are euhedral to skeletal poikiloblasts with abundant inclusions of hornblende, plagioclase, quartz, opaque minerals, and epidote. A second population of garnet grains occurs as clusters of euhedral grains.

Metamafic rocks also occur in this area, as interlayers within the metapelitic rocks described above. These are dense, fine grained, granoblastic rocks consisting mainly of blue-green hornblende and calcic plagioclase, but they also contain garnet, opaque oxide minerals, and minor amounts of epidote group minerals, titanite, and in one section, biotite.

Mafic metavolcanic rocks were collected from an area in the Clayton quadrangle mapped as garnet-muscovite-biotite schist by Carpenter and others (1998b). These rocks are interlayered with pelitic schists. The medium to coarse-grained mafic rocks are banded on the mm to cm scale. Bands consist of garnet-rich layers and amphibole-rich layers. Garnet-rich layers contain euhedral to subhedral garnets with inclusion trails of quartz, having orientations oblique to the hornblende layering. Anhedral garnet poikiloblasts have very irregular boundaries. Some of the anhedral or skeletal garnets are bound by multiple, small euhedral garnet grains, suggesting two phases of growth. Inclusions in the anhedral garnets are quartz, zoisite, and titanite. Many garnet grains remain only as euhedral skeletal rims, surrounding a mixture of quartz and lesser amounts of opaque minerals, plagioclase and hornblende. The garnet layers have a quartz and plagioclase-rich fine granoblastic matrix. Diopside poikiloblasts are found within the garnet-quartz layers. These commonly partly enclose garnets. Small- to medium-sized prismatic zoisite grains are randomly distributed in these layers.

One outcrop of massive mafic metavolcanic rock interlayered with pelitic schist was sampled along Mill Creek (Figure 2). It has weak foliation defined by the planar alignment of elongate to acicular grains of orthoamphibole (gedrite) and hornblende. These rocks contain some anhedral garnet (Figure 3h), and have a matrix of anhedral, fine-grained quartz and untwinned plagioclase. Minor amounts of ilmenite are scattered throughout these samples.

MINERAL CHEMISTRY

Representative mineral analyses are presented in Table 2. All individual analyses may be found in Gaughan (1999) or Stoddard (1992).

Garnet

All garnets are Al-rich, as andradite contents range only from 0 to 2 mole percent. The majority of the garnet grains analyzed are almandine rich, with lower spessartine, pyrope and grossular components (Figures 4 and 5). Magnesium content is low in all garnets analyzed from metapelitic rocks (Figure 4), but Fe and Mn contents are variable. Garnets from the Bunn (BE) area have the highest average Fe content ($alm_{72.5-84.4}$) and lowest average Mn content ($sps_{3.6-14.1}$). Garnets in the remainder of the

Table 2. Selected analyses of garnet, biotite, plagioclase, and amphibole.

mineral	garnet	garnet	garnet	garnet	garnet	garnet	garnet	garnet
area	E D	B E	FL-MC	FL-HC	FL-MC	C L	B E	B E
sample #	c 1-198	BEA-4	FL-10	FLA-5	FL-14	CL-2A	BE-320A	BE-616A
lithology	pelitic	pelitic	pelitic	pelitic?	mafic	mafic	mafic	mafic
	rim	rim						
SiO_2	36.75	37.16	36.82	36.42	36.91	37.38	36.84	37.44
Al_2O_3	21.52	21.29	21.90	20.69	21.72	22.00	21.07	21.20
TiO_2	0.07	0.02	0.01	0.07	0.05	0.08	0.03	0.12
FeO	25.35	36.23	28.02	2.25	34.00	21.56	24.31	23.27
MnO	14.04	2.07	9.22	37.25	2.09	8.55	10.31	7.90
MgO	1.91	2.58	3.15	0.78	3.24	1.43	1.82	0.93
CaO	1.38	1.53	1.53	2.91	2.84	9.95	6.90	10.74
Na_2O	0.04	0.01	0.01	0.00	0.03	0.03	0.00	0.00
total	101.06	100.89	100.66	100.37	100.88	100.98	101.28	101.60
# oxy	12	12	12	12	12	12	12	12
Si	2.96	2.98	2.95	2.97	2.94	2.95	2.94	2.96
Al^{iv}	2.04	2.01	2.07	1.99	2.04	2.05	1.98	1.98
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01
Fe	1.71	2.43	1.88	0.15	2.27	1.42	1.59	1.51
Mn	0.96	0.14	0.62	2.57	0.14	0.57	0.70	0.53
Mg	0.23	0.31	0.38	0.09	0.39	0.17	0.22	0.11
Ca	0.12	0.13	0.13	0.25	0.24	0.84	0.59	0.91
mol %								
alm	56.66	80.67	62.36	3.64	74.50	47.37	51.50	49.40
and	0.00	0.50	0.00	2.00	1.00	0.00	0.00	0.00
gros	3.95	4.28	4.36	6.28	6.95	28.01	19.00	29.70
prp	7.61	10.33	12.50	2.98	12.91	5.60	7.00	3.60
sps	31.78	4.67	20.78	85.10	4.64	19.03	22.50	17.30

mineral	biotite	biotite	biotite
area	E D	B E	FL-MC
sample #	c 1-198	BEA-4	FL-10
lithology	pelitic	pelitic	pelitic
SiO_2	33.84	34.16	35.52
Al_2O_3	18.59	19.94	18.82
TiO_2	1.80	1.81	1.73
FeO	19.65	21.50	17.89
MnO	0.28	0.05	0.14
MgO	10.45	9.13	11.10
CaO	0.03	0.01	0.01
Na_2O	0.04	0.18	0.00
K_2O	8.98	7.62	10.14
total	93.66	94.40	95.35
# oxy	22	22	22
Si	5.27	5.26	5.39
Al^{iv}	2.73	2.74	2.61
Al^{vi}	0.68	0.87	0.75
Ti	0.21	0.21	0.20
Fe	2.56	2.77	2.27
Mn	0.04	0.01	0.02
Mg	2.43	2.09	2.51
Ca	0.01	0.00	0.00
Na	0.01	0.05	0.00
K	1.78	1.50	1.96
total	15.71	15.50	15.71
Mg/Mg+Fe	0.49	0.43	0.53

mineral	plag	plag	plag	plag
area	E D	B E	FL-MC	FL-HC
sample #	c 1-198	BEA-4	FL-10	FLA-5
lithology	pelitic	pelitic	pelitic	pelitic?
SiO_2	60.48	60.59	59.69	59.75
Al_2O_3	25.47	25.53	25.77	25.87
FeO	0.14	0.17	0.13	0.08
CaO	5.27	5.35	6.73	5.72
Na_2O	8.40	8.52	8.25	8.69
K_2O	0.05	0.03	0.07	0.15
total	99.81	100.19	100.64	100.26
# oxy	8	8	8	8
Si	2.69	2.69	2.65	2.66
Al^{iv}	1.33	1.33	1.35	1.36
Fe^{3+}	0.01	0.01	0.00	0.00
Ca	0.25	0.25	0.32	0.27
Na	0.72	0.73	0.71	0.75
K	0.00	0.00	0.00	0.01
total	5	5.01	5.03	5.04
mol% *An*	25.8	25.8	31.1	26.7

mineral	plag	plag	plag	plag
area	FL-MC	C L	B E	B E
sample #	FL-14	CL-2A	BE-320A	BE-616A
lithology	mafic	mafic	mafic	mafic
SiO_2	53.39	42.62	45.43	42.57
Al_2O_3	30.03	37.93	35.57	37.10
FeO	0.05	0.28	0.10	0.05
CaO	10.68	19.06	18.16	19.95
Na_2O	5.84	0.46	1.18	0.34
K_2O	0.04	0.00	0.02	0.00
total	100.03	100.35	100.46	100.01
# oxy	8	8	8	8
Si	2.41	1.97	2.08	1.97
Al^{iv}	1.60	2.06	1.92	2.03
Fe^{3+}	0.00	0.01	0.00	0.00
Ca	0.52	0.94	0.89	0.99
Na	0.51	0.04	0.11	0.03
K	0.00	0.00	0.00	0.00
total	5.04	5.02	5.00	5.02
mol% *An*	50.3	95.8	89.4	97.0

mineral	amphib	amphib	amphib	amphib	amphib
area	FL-MC	FL-MC	C L	B E	B E
sample #	FL-14	FL-14	CL-2A	BE-320A	BE-616A
lithology	mafic	mafic	mafic	mafic	mafic
SiO_2	39.95	39.26	49.92	40.69	45.39
Al_2O_3	17.68	18.99	5.62	15.19	11.18
TiO_2	0.16	0.24	0.24	0.61	0.32
FeO	27.53	19.73	13.99	20.33	19.42
MnO	0.45	0.23	0.44	0.59	0.27
MgO	9.19	6.27	13.89	7.06	7.27
CaO	0.47	9.94	12.06	11.32	12.07
Na_2O	1.76	1.57	0.30	1.08	0.58
K_2O	0.01	0.22	0.07	0.87	0.22
total	97.20	96.45	96.53	97.74	96.72
# oxy	23	23	23	23	23
Si	6.10	5.99	7.35	6.20	6.81
Al^{iv}	1.90	2.01	0.65	1.80	1.19
Al^{vi}	1.28	1.40	0.33	0.93	0.78
Ti	0.02	0.03	0.03	0.07	0.04
Fe	3.51	2.52	1.72	2.59	2.44
Mn	0.06	0.03	0.05	0.08	0.03
Mg	2.09	1.43	3.05	1.60	1.83
Ca	0.08	1.62	1.90	1.85	1.94
Na	0.52	0.46	0.09	0.32	0.17
K	0.00	0.04	0.01	0.17	0.04
total	15.56	15.53	15.18	15.61	15.27
Mg/Mg+Fe	0.37	0.36	0.64	0.38	0.43

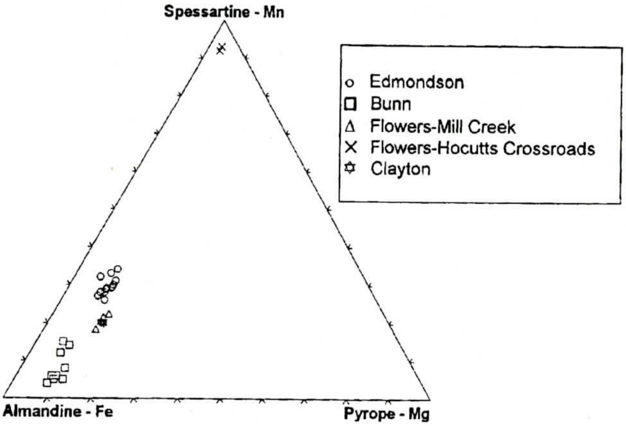


Figure 4. Variation in the composition of garnets in metapelitic rocks from each locality, with respect to Fe, Mg, and Mn. All garnets are Al-rich (pyralspite series). Sample location areas indicated by symbols as shown.

metapelitic rocks have relatively high spessartine components, from the Clayton (CL) and Mill Creek (MC) metapelitic rocks ($sps_{17.6\text{-}20.9}$) to the Edmondson (ED) samples ($sps_{23.4\text{-}32.7}$). The Hocutts Crossroads (HC) samples contain a few Mn-rich, Fe-poor garnets with compositions unusual for metapelitic rocks ($sps_{84\text{-}85}$; $alm_{<5}$). Disequilibrium textures, described above, suggest that these garnets may not represent peak metamorphic compositions.

Some garnets in the ED and BE samples are zoned, with greater Fe and lower Mn in rims than in cores. This Fe-Mn zoning suggests scavenging of available Mn during early garnet growth, perhaps at lower temperatures than those required for growth of Fe-rich garnet (Yardley, 1989, p.162). Several garnets from ED samples display "inverse zoning" (Dietvorst, 1982), with cores richer in Fe and rims richer in Mn. All zoned ED garnets have cores richer in Mg than rims. There is no obvious correlation between garnet morphology and composition in the specimens analyzed.

Compositions of garnets from metamafic samples are plotted in Figure 5. They are Mg-poor Fe-Ca-Mn Al-garnets; most are unzoned.

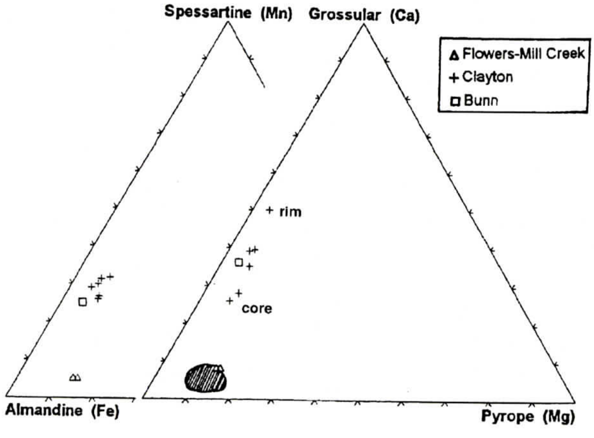


Figure 5. Mafic rock garnet compositions plotted in terms of Fe-Mn-Mg variation (left) and Fe-Ca-Mg variation (right). The Clayton garnets with the highest and lowest Ca content are from rim and core analyses, respectively. Shaded area shows the range of compositions for garnets from metapelitic rocks in this study, for comparison. Sample location areas indicated by symbols as shown.

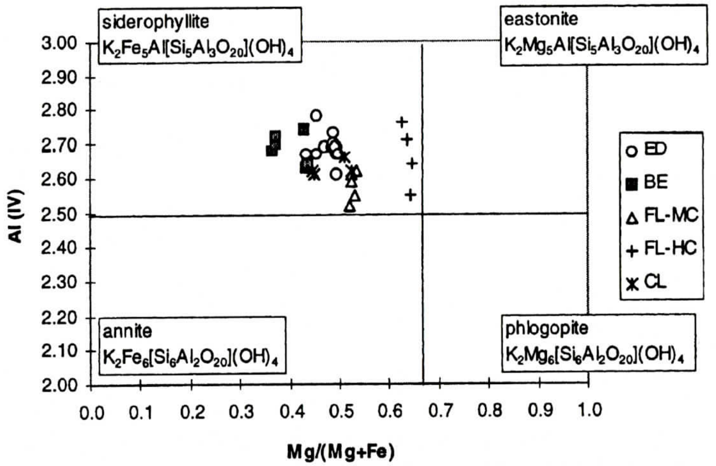


Figure 6. Molecular percent Mg/(Mg+Fe) vs. number of tetrahedral Al cations (per 22 oxygens) in biotite from metapelitic samples. Biotite classification after Deer and others (1966). Sample location areas indicated by symbols as shown. ED: Edmondson; BE: Bunn; FL-MC: Mill Creek; FL-HC: Hocutts Crossroads; CL: Clayton.

One FL sample contains garnet that is primarily almandine ($alm_{74.5-75.2}$) with lower pyrope ($prp_{12.4-12.9}$) content, and is typical of metamorphosed Fe-rich mafic rocks (Spear, 1993, p.413). For comparison, a garnet composition from one BE metabasalt sample is included on Figure 5 (analysis by Stoddard, 1992). This garnet is an alm-sps-grs mixture, with very low Mg content ($prp_{<0.07}$). Garnets from one of the CL samples have a greater Mn component ($sps_{16.6-25.4}$), and a significantly higher Ca content ($grs_{19.3-41.4}$) than those in the other metamafic rocks. These CL garnets have < 6% pyrope component. In this sample, garnet grains with visibly distinct cores and rims display significant zoning, with Ca-rich rims and Fe-rich cores, as shown in Figure 5.

Sheet Silicates

Biotite was analyzed in all metapelitic samples. All analyzed biotite grains plot within the siderophyllite field ($Al^{IV} > 2.5$), just slightly out of the annite range (Figure 6). The Fe and Mg contents of biotites vary with location. Biotites in the BE and ED samples have the lowest Mg content, those from the CL and MC samples are higher, and those from the HC sample are highest. The lack of a consistent temperature trend (see Thermobarometry, below) with varying Mg/(Mg+Fe) ratios (from 0.37 to 0.65) suggests that Mg/(Mg+Fe) ratios may reflect differences in bulk rock composition more than differences in metamorphic grade. White mica from all metapelitic samples falls within the true muscovite field ($K_{1.52-1.80}$), with a small paragonite component ($Na_{.10-.34}$).

Plagioclase

Plagioclase from metapelitic samples is nearly all oligoclase, with an An range of $An_{16.2-31.1}$. Plagioclase in the MC samples has the highest Ca content, with some analyses falling on the oligoclase-andesine boundary. The ED, BE, CL and HC samples have similar and overlapping compositions. Some plagioclase from the ED rocks is zoned, with cores more Ca-rich than rims. Plagioclase zoning was not observed in any of the other metapelitic samples examined. The MC plagioclase compositions, and the presence of minor epidote in some samples indicates that the MC rocks have a protolith chemistry richer in Ca than the other metapelitic rocks.

One mafic MC sample contains plagioclase within the andesine to labradorite range ($an_{45.3-59.4}$), with individual grains having cores richer

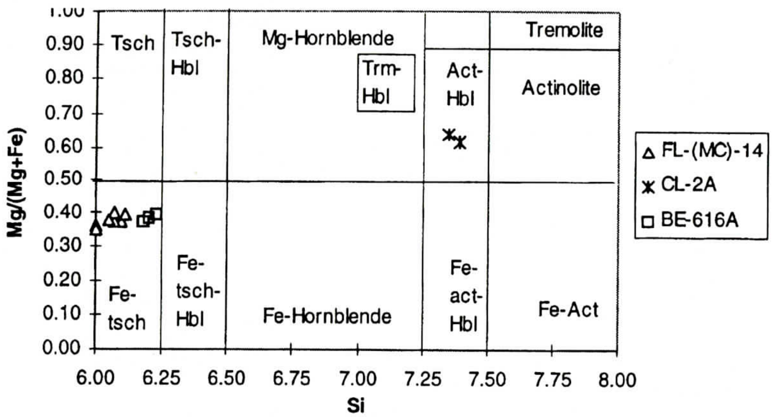


Figure 7. Molecular percent Mg/(Mg+Fe) vs. number of Si cations (per 23 oxygens) in calcic amphiboles from metamafic rocks (cations per 23 oxygens; classification after Leake, 1978). Sample location area as in Figure 6.

in Ca than rims. This composition range is consistent with a mafic volcanic protolith, at moderate grades of metamorphism (Winkler, 1979, p.172). Plagioclase from the other mafic samples is unusually Ca-rich. For example, those from the BE area lie within the bytownite-anorthite range (Stoddard, 1992). Sample CL-2A contains abundant small grains of nearly pure anorthite ($an_{95.3-96.5}$) throughout the matrix. No zoning was detected in the Ca-rich grains analyzed.

Amphibole

Amphibole is abundant in mafic samples. One MC sample contains both calcic hornblende of the ferrotschermakite series and the orthoamphibole gedrite (Figure 7). The hornblende has Mg/(Mg+Fe) ratio of 0.35-0.38, and the gedrite has a similar ratio of 0.37-0.40. Amphibole in mafic BE samples (Stoddard, 1992) is Fe-tschermakite similar in composition to those from MC. Amphibole in a CL sample is Al-poor calcic hornblende with high Si and Mg contents, and plots within the actinolitic hornblende field in Figure 7. No zoning was observed within any of the amphibole grains analyzed.

Pyroxene

Pyroxene is present only in mafic samples from the Clayton area. All analyzed grains have compositions along the diopside-hedenbergite join (0.97 – 0.98 cations Ca per six oxygens) with fairly high Mg/(Mg+Fe) ratios of 0.63-0.66. The Mg/Fe ratios are comparable to those of amphibole from the same sample.

Other Minerals

Staurolite grains were analyzed from ED, BE and CL metapelitic samples. All staurolite grains analyzed are Fe-rich (Mg/(Mg+Fe) < 20%). ZnO content in ED grains is < 0.75% by weight. Opaque oxide minerals from selected samples were analyzed for identification purposes. ED, MC and CL metapelitic rocks contain scattered, fine grains of nearly pure ilmenite. HC samples contain prominent, volumetrically significant magnetite, but some spot analyses have significant Ti content, perhaps because of patchy exsolution (Haggerty, 1991, p.130-134).

MINERAL ASSEMBLAGES AND PETROGENETIC INTERPRETATION

Metapelitic Rocks

The mineral assemblages (Table 1) in the metapelitic rocks are equivalent to those of Pattison and Tracy's (1991) facies series 2. In this classification system, sub-facies series type 2b

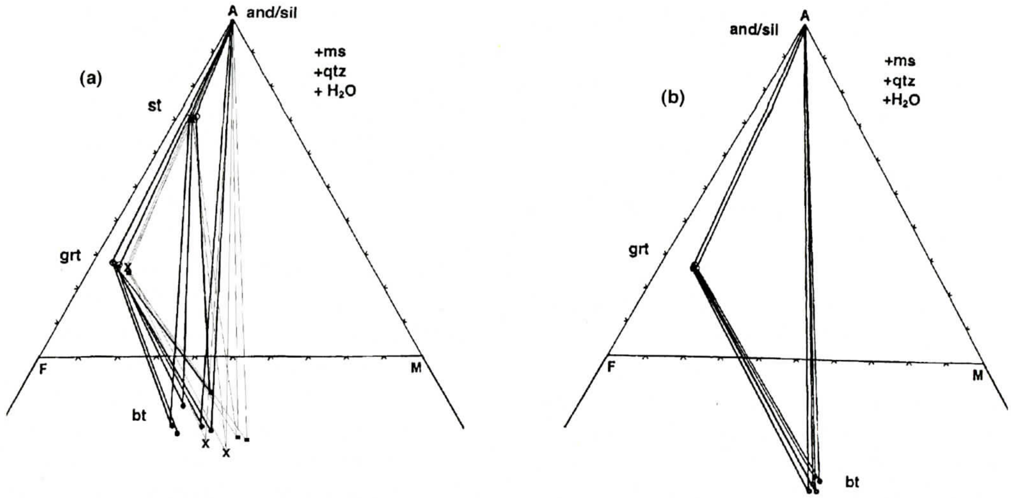


Figure 8. (a) AFM projection for metapelitic samples from the Bunn, Edmondson, and Clayton areas. F = Fe+Mn. In Bunn and Edmondson, assemblage is grt + bt + st ± and; fibrolitic sillimanite replaces andalusite in Clayton samples. (b) AFM projection for metapelitic samples from the Mill Creek area. F = Fe+Mn. Assemblage is grt + bt ± and ± sil. All sillimanite is fibrolitic. Relict chloritoid and possible pseudomorphs after staurolite are not included.

is characterized by the predominance of staurolite with andalusite at low to intermediate grades. All metapelitic rocks examined in this study belong to this subfacies series type.

Bunn, Edmondson, and Clayton

In the Bunn, Edmondson, and Clayton areas, metapelitic rocks, mapped as argillite outside the aureole, have developed abundant porphyroblasts of garnet and staurolite, and local andalusite within 1.5 km of the batholith. They exhibit relatively coarse porphyroblastic textures, clearly indicating higher metamorphic temperatures than the biotite-zone rocks that occur at a greater distance from the contact (Stoddard, 1992; Carpenter and others, 1995). Trails of mineral inclusions in garnet and staurolite are typically oblique to the matrix foliation, suggesting that these grains preserve an earlier rock fabric, possibly related to regional low-grade metamorphism.

AFM projections show excess phases (i.e. crossing tie-lines) within the K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (KFMASH) system (Figure 8a). This is likely a result of the presence of additional components outside the simple KFMASH system, including Ti in biotite and Mn in garnet. The presence of these components is at least partly the result of differences in rock composition, but is also influenced by other factors such as oxygen fugacity. These components extend both the lower and upper temperature stability bounds of minerals plotted.

Euhedral cores of numerous staurolite grains are inclusion-free, whereas rims and other skeletal and poikiloblastic staurolite grains preserve the matrix crenulation and seem to have grown simultaneously with fabric development. Although such textures suggest that staurolite growth occurred in two phases, no significant differences in composition were observed (Gaughan, 1999). Typically, euhedral staurolite and large biotite grains both enclose garnet in these rocks, indicating the earlier growth of garnet (Figure 3a, b). The following reaction (reaction y on Figure 11b) can explain these relationships:

grt + chl ± ms ± qtz o st + bt + H_2O ± qtz

(Yardley, 1989; Pattison and Tracy, 1991; Spear, 1993). The presence of several kinked biotite porphyroblasts in the Bunn samples suggests that, in that area, biotite, like staurolite, grew at least partially synkinematically.

Euhedral andalusite porphyroblasts in most samples indicate final metamorphic equilibration of samples at relatively low pressures, within the lower pressure range of the staurolite zone (Yardley, 1989). This mineral was likely the last porphyroblast phase, and may have been produced through the reaction (z on Figure 11b):

ms + qtz ± chl ± st → and + bt + H_2O

(Thompson and Norton, 1968). The possibility that staurolite was consumed in this reaction is suggested by the fact that staurolite grains occur partially within andalusite in some samples. Finally, some andalusite grains are replaced, partially or completely, by unoriented coarse-grained white mica (Figures 3c, d), locally preserving a chiastolite form. This replacement may be the result of the introduction of K^+ associated with late magmatic aqueous fluids derived from the intruding granite, through the reaction:

K^+ + and + qtz + H_2O → ms + H^+ (Dickerson and Holdaway, 1989).

The metamorphic conditions recorded in these samples are below those for the breakdown of staurolite and muscovite in the presence of quartz, as these are both prominent and apparently stable phases. Although some staurolite may have been consumed to form andalusite, none of the samples has reached a staurolite-out isograd.

Mill Creek and Hocutts Crossroads

Because of the presence of fibrolitic sillimanite and the absence of staurolite in rocks from these two areas, metamorphic temperatures are thought to have been somewhat higher than in the other areas. In addition, plagioclase from metapelitic rocks in these areas has higher Ca-content than in the other areas, suggesting either a higher temperature or a different protolith chemistry.

In one sample, from within 300m of the pluton margin, chloritoid is present as small corroded grains surrounded by muscovite. It is interpreted as a relict phase.

Quartz and muscovite-rich samples contain prominent porphyroblasts of andalusite, partially replaced by fibrolitic sillimanite, suggesting conditions near the andalusite – sillimanite polymorphic transition. Formation of the sillimanite could be the result of this reaction, or it may have formed independently from the fine-grained white mica that replaces andalusite:

ms → sil + qtz + H_2O + K^+.

In a study of the Ardara and Fanad aureoles, Kerrick (1987) found fibrolitic sillimanite + biotite intergrowths in rocks that showed no evidence of the earlier presence of andalusite. He inferred that fibrolitic sillimanite grew metastably in the andalusite field from biotite breakdown ("fibrolitized biotite"). Such an origin for sillimanite in the HC samples is possible. However, some biotite (and muscovite) in these rocks appears robust and unassociated with sillimanite. In his study, Kerrick (1987) noted an absence of opaque minerals, and inferred that K, Mg, and Fe were released in a fluid phase. In the HC samples, the abundant Ti-magnetite may account for the fate of Fe and Ti ions. Similar to the Ardara aureole, the HC samples show evidence of late-stage muscovite formation, and both areas have tourmaline as a prominent accessory mineral. Both features may be related to the influx of fluids from the cooling intrusion.

Sparse garnets in HC samples are nearly pure spessartine in composition. Garnets of this composition are not common in metapelitic rocks and their origin in these rocks is unclear. It is possible that they formed by partial dissolution of initially almandine-rich garnets. Remaining garnet would be enriched in Mn as a consequence. Fe ions from the original (inferred) garnet may have been taken up in biotite, or magnetite through the reaction:

$grt_{alm} + O_2$ → mag + Al_2SiO_5 + qtz.

Despite the fact that the garnet is high in Mn, the mineral occurs as such a sparse phase that this does not necessitate a Mn-rich protolith.

Figure 8b is an AFM diagram for the MC samples. The HC samples are not portrayed because of their high Mn, low Fe and Mg garnet compositions. These garnets also make thermobarometry inappropriate. Published thermobarometric models involving garnet do not account for garnets so rich in Mn, because of uncertainty in activity-composition models for Mn. Furthermore, if the dissolution model pre-

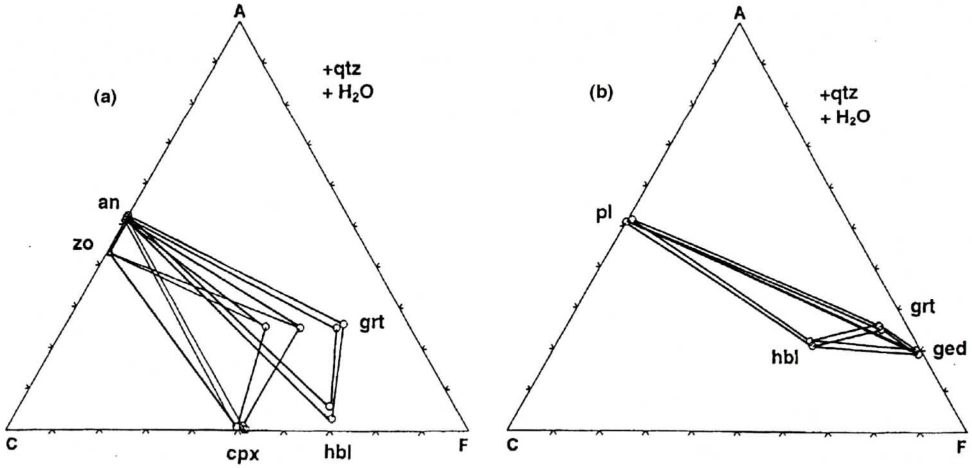


Figure 9. (a) ACF diagram for metamafic samples (CL-2A) from the Clayton area. Layered rocks contain two distinct assemblages: grt + cpx + an + zo; hbl + grt + an. Significant Mn content (sps16.6-25.4) stabilizes garnet in both assemblages. (b) ACF diagram for metamafic samples (FL-(MC)-14) from the Mill Creek area. Assemblage is hbl + ged + grt + pl. Note crossing tie-lines suggest that the reaction: pl + ged □⇗grt + hbl may have occurred.

sented above is correct, then it is likely that this garnet composition is not representative of peak equilibrium conditions.

Mafic Metavolcanic Rocks

Figure 9a is an ACF diagram for the CL metamafic samples. Garnet is abundant, and many garnet grains have inclusion trails oblique to the rock fabric, preserving an earlier foliation. Two stages of garnet growth are suggested by distinct Ca-rich rims with Fe-and Mn-rich cores, as well as by some skeletal poikiloblastic grains surrounded by multiple euhedral garnets. Ca-rich rims suggest growth during breakdown of another Ca phase, possibly an epidote group mineral. Diopside and minor zoisite occur together in garnet-rich, hornblende-free layers, reflecting differences in bulk composition.

Figure 9b is an ACF diagram for the MC metamafic samples. Occurrence of the orthoamphibole gedrite suggests relatively low pressure – high temperature conditions within the hornblende hornfels or low pressure amphibolite facies. At these conditions, there is little substitution of Al for Fe and Mg in octahedral hornblende sites (Yardley, 1989). Al is therefore used to make more modal An-rich plagioclase, leaving less Ca for amphibole, and thus resulting in development of Fe-Mg orthoamphibole.

Plagioclase composition may be a crude indicator of metamorphic grade in amphibolites, although much uncertainty is associated with this method (Winkler, 1979). Plagioclase in the MC samples is andesine-labradorite (an$_{45-60}$), which as part of the association alm + pl + hbl + Ca-free amphibole, is reported to represent high-temperature, medium grade conditions (Winkler, 1979). Plagioclase in CL rocks is anorthite (an$_{95-96}$), suggesting an unusually Ca-rich, Na-poor rock composition.

Summary and Implications

Samples from the Edmondson area represent the outer aureole and show static andalusite growth overprinting a foliation interpreted to represent earlier regional lower greenschist facies conditions (Figures 3e,f). In samples from the Bunn, Mill Creek, and Clayton areas, porphyroblasts appear syn- to post-deformational with respect to matrix fabrics (Figure 3a); possible earlier fabrics are locally preserved in garnet and staurolite porphyroblasts. Some samples display two textural populations of garnet, staurolite, biotite or combinations of these

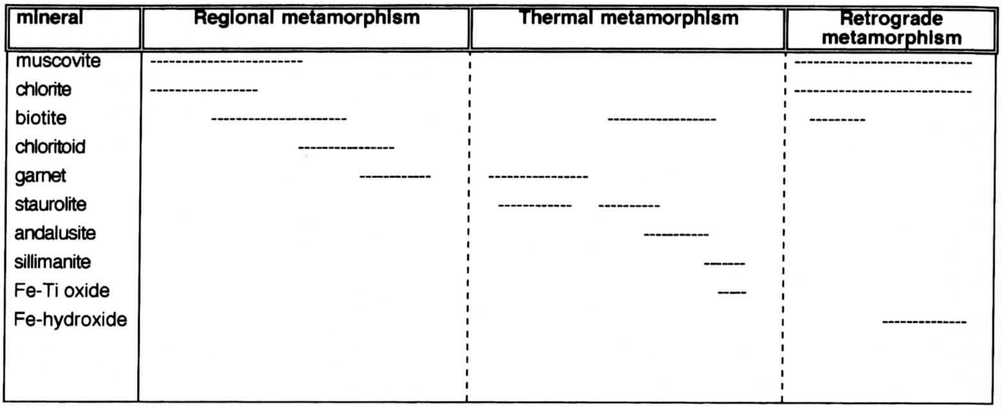


Figure 10. Inferred sequence of mineral growth for Spring Hope terrane metapelitic samples discussed in the text. Time evolves toward the right. Regional metamorphism precedes thermal overprint that accompanied pluton intrusion. Retrograde mineral growth occurred after pluton emplacement, and accompanied uplift and cooling. Retrograde minerals replace earlier minerals. More than one growth episode is inferred for several minerals.

minerals, suggesting two periods of growth. These observations may suggest either: (1) separate peaks for Alleghanian regional metamorphism and thermal metamorphism; or (2) a separate medium-grade regional metamorphic and deformational event, occurring prior to the Alleghanian orogeny. Following the metamorphic peak(s), local late-stage retrograde metamorphism accompanied uplift and cooling. Figure 10 summarizes the inferred sequence of mineral growth and texture development for metapelitic rocks.

THERMOBAROMETRY

Geothermometers and geobarometers have been widely used to reconstruct metamorphic histories and pressure-temperature-time (P-T-t) paths within orogenic belts. Determining the P-T environment of pluton emplacement can also provide information on the thermal evolution of an orogenic belt, allowing for a better understanding of the late orogenic stages that commonly include extensive crustal melting and emplacement of granitic magmas (Montel and others, 1992). Metapelitic and mafic country rocks adjacent to the Rolesville batholith provide the opportunity to define the conditions of emplacement through the use of petrogenetic grids and thermobarometric calculations.

Petrogenetic Grids

The KFMASH petrogenetic grid accounts for reactions in the system K_2O -FeO-MgO-Al_2O_3-SiO_2-H_2O and is a tool commonly used for the interpretation of metamorphosed pelitic rocks. Spear and Cheney's quantitative petrogenetic grid (1989; Figure 11) is based on thermodynamic data of Berman (1988), with P-T slopes of endmember reactions calculated using the Gibbs method. Quartz and muscovite are assumed to be in excess. This grid includes garnet, biotite, staurolite, chloritoid, and Al_2SiO_5 polymorphs, and thus can be used to plot mineral assemblages of metapelitic samples from this study.

The metapelitic samples from the Mill Creek (MC) area represent slightly higher temperatures within the diagonally striped region of Figure 11, owing to the presence of local sillimanite, and the inferred breakdown of staurolite (reaction z in Figure 11b). The HC samples indicate a still higher temperature (cross-hatched region of Figure 11), evidenced by the occurrence of widespread sillimanite, breakdown of garnet, and complete disappearance of staurolite. None of the samples studied have reached the temperature of muscovite breakdown (640° at 3 kbar). Because of the slope of the andalusite-sillimanite curve, the presence of silli-

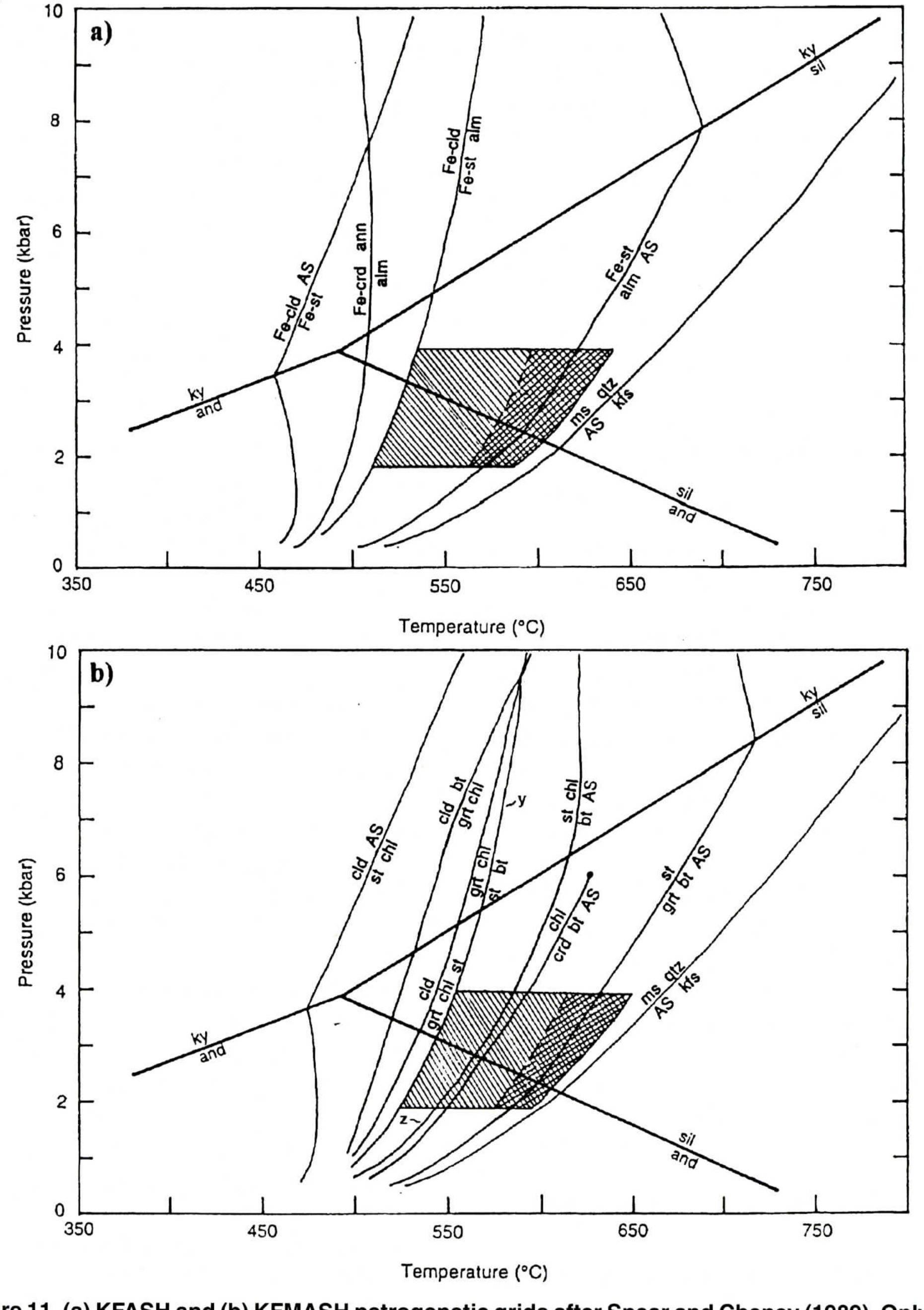


Figure 11. (a) KFASH and (b) KFMASH petrogenetic grids after Spear and Cheney (1989). Only pertinent equilibria are shown. Shaded regions indicate suggested P-T range for samples from this study. Diagonally striped regions: grt + bt + st ± and ± sil assemblages (BE, CL, FL-MC, ED areas). Cross-hatched regions: grt + bt + sil assemblages (FL-HC area).

manite may also indicate a slight increase in pressure for samples from the HC area. Metapelitic rocks from the Bunn (BE), Edmondson (ED) and Clayton (CL) areas contain the assemblage grt-bt-st-and-ms-qtz and therefore plot within a single field on the KFASH and

KFMASH diagrams, as indicated in Figure 11. A temperature minimum is established by the presence of staurolite, from the reaction grt + chl → st + bt, appearing at approximately 525-550°C (at pressures >2 kbar). The andalusite-sillimanite univariant curve limits pressure to below about 3.9 kbar, the Al_2SiO_5 triple point of Berman (1988). Mn and Ca enlarge the stability field of garnet by 30°C for every 10 mole% spessartine, or spessartine + grossular (Spear and Cheney, 1989). Significant Mn content in garnet from numerous samples (to a maximum of sps_{33} in the ED metapelitic rocks, excluding garnet from the Hocutts Crossroads (HC) samples) allows garnet to form at temperatures as low as 435°C (at 3 kbar) and to persist throughout the staurolite zone.

Unfortunately, considerable uncertainty still exists concerning the stability fields for the Al_2SiO_5 minerals, particularly the location of the andalusite-sillimanite phase boundary (Anderson and others, 1977; Hodges and Spear, 1982; Holdaway and Mukhopadhyay, 1993). Salje (1986) reported a narrow stability field for fibrolitic sillimanite, occurring at higher metamorphic grades than prismatic sillimanite. Conversely, numerous studies have reported the occurrence of fibrolitic sillimanite in nature over a wider P-T range than for prismatic sillimanite (Yardley, 1989, p.85). As noted above, Kerrick (1987) described metapelitic rocks in which fibrolitic sillimanite was formed metastably at conditions apparently within the andalusite stability field. Trace elements within fibrolitic sillimanite may also have some effect on its stability, although this effect has not been well characterized (Kerrick and Speer, 1988).

Thermobarometric Calculations

Temperature and pressure of metamorphism may be calculated directly based on the T- and P-dependent equilibrium constant (K_{eq}), using mineral compositional data from equilibrium assemblages, and the computer program *Thermobarometry* (Spear, 1995; Gaughan, 1999). Results are listed in Table 3. In each case, the K_{eq} lines intersect to define a unique point in P-T space; to account for uncertainty, this single point may more correctly be expanded to a field centered about the point.

Metapelitic Rocks

The garnet-biotite Fe-Mg cation exchange reaction (alm + phl = prp + ann) has been widely used for metapelitic rocks, and numerous calibrations exist that produce different results. Various calibrations of the grt-bt geothermometer result in calculated temperature differences of up to 70°C on individual samples from this study (Gaughan, 1999). Because of the high Mn content of most garnets in the metapelitic samples reported here, the Ganguly and Saxena (1984) calibration has been used, as it includes corrections for non-ideal mixing of Mn and Ca in garnet. Although this calibration has been reported to produce unrealistically high temperature (and therefore pressure) results in some cases (Applegate and Hodges, 1994), it yielded acceptable results for nearly all samples in this study.

Temperatures for all metapelitic rocks analyzed fall between 518° and 618°C, with no significant differences between sample areas (Table 3a). The ED and BE samples have the largest temperature range, probably a result of the relatively large number of samples analyzed. Some distinction can be made, however, between individual samples within a single area. Edmondson drill cores 2 and 4 yield the highest temperatures from this area, all near or higher than 550°C. Cores 1 and 3 yield lower temperatures (from 518°-548°C), that appear to correspond with their slightly greater distance from the pluton. Temperatures as low as 525° may represent some re-equilibration between garnet and biotite. This suggestion is supported by zoning in several garnet grains. Temperatures from ED samples 2 and 4, particularly from garnet cores, are inferred to be more accurate representations of peak conditions in this area, because of the possibility of late-stage diffusion in rims. In the BE area, samples BEA-1 and 2 give the highest temperatures (579°-618°C). Lower temperatures from other samples may indicate re-equilibration between garnet and biotite, even where no textural evidence of disequilibrium was observed.

Table 3a. Results from thermobarometric calculations for metapelitic rocks. Uncertainties are estimated at ± 32°C and ± 0.3 kbar. See Gaughan (1999) for details. The grt-ky schist is from the Crabtree terrane; analyses of Speer (1994b) were used. Calibrations are from Ganguly and Saxena (1984). Garnet core and rim analyses are noted where used.

sample	Approximate intersection grt-bt T (°C)	GASP P (kbar)
ED 1-198 (grt rim)	522	2.9
ED 1-198 (grt core)	547	1.8
ED 2-37	550	1.9
ED 2-37 (grt core)	565	1.2
ED 2-37	547	1.6
ED 2-250	574	1.6
ED 3-26 (grt rim)	518	1.3
ED 3-26 (grt core)	548	1.7
ED 3-250	525	2.2
ED 3-250	535	1.9
ED 4-43	611	2.7
ED 4-43	579	2.8
ED 4-138 (grt core)	593	1.8
ED 4-138	568	1.9
ED 4-250	578	2.9
ED 4-250 (grt core)	594	2.5
BEA-1	609	2.1
BEA-1	594	1.3
BEA-2	579	1.9
BEA-2 (grt core)	618	4.4
BEA-3	540	2.9
BEA-3	524	3.0
BEA-4 (grt rim)	566	2.1
BEA-4 (grt core)	547	1.5
BEA-5	577	1.9
BEA-5	553	3.6
BEA-5	573	3.0
FL-(MC)-10	576	3.3
FL-(MC)-10	574	2.6
FL-(MC)-10 (grt rim)	531	1.4
FL-(MC)-10 (grt core)	562	2.8
FL-(MC)-10	540	2.2
CL-6A (grt core)	571	3.6
CL-6A	548	3.1
grt-ky schist (grt core)	572	7.9
grt-ky schist (grt core)	644	7.9
grt-ky schist (grt rim)	610	5.9

Table 3b. Results from thermobarometric calculations for metamafic rocks. BE-320A is from a dominantly felsic metavolcanic unit, located approximately 6 km NNE of the other BE samples. Calibrations are (1) Graham and Powell (1984) grt-hbl thermometer; (2) Kohn and Spear (1990), Fe-tschermakite model, grt-pl-hbl-qtz barometer; (3) Powell and Holland (1985) grt-cpx thermometer; (4) Powell and Holland (1988) grt-pl-cpx-qtz barometer, with Hodges and Spear garnet model.

Sample	Approximate intersection grt-hbl[1] T (°C)	grt-pl-hbl-qtz[2] P (kbar)
FL-(MC)-14	597	3.5
FL-(MC)-14	591	3.1
FL-(MC)-14	590	3.3
FL-(MC)-14	580	3.3
CL-2A	496	2.5
CL-2A	457	2.6
CL-2A	509	3.2
BE-616A	537	3.9
BE-320A	610	3.8

Sample	grt-cpx[3] T (°C)	grt-pl-cpx-qtz[4] P (kbar)
CL-2A	556	2.1
CL-2A	538	1.9
CL-2A	578	3.0

Samples FL-(MC)-10 and CL-6A give temperature results in the middle of the larger range determined from ED and BE samples. Temperatures within sample FL-(MC)-10 range from 531° to 576°C. In this sample, the rim of a zoned garnet grain gives the lowest temperature result (531°), and the core yields a temperature approximately 30° higher (562°). Excluding garnet rim results, the temperatures are more consistent (562°-576°), and are interpreted to represent peak temperatures. Sample CL-6A gives temperatures very similar to those of FL-

(MC)-10, with a maximum core temperature of 571°, and a lower temperature of 548° from an averaged garnet composition.

The net transfer reaction: an = grs + Al_2SiO_5 + qtz (GASP) is a barometer commonly used for metapelitic rocks containing an aluminum silicate polymorph. However, it is based on the Ca endmembers for plagioclase and garnet, and thus additional uncertainty is introduced with low Ca garnet and plagioclase. The GASP geobarometer with the calibration of Ganguly and Saxena (1984) was used in this study. ED samples yield pressures of 1.2-2.9 kbar (average = 2.1 kbar). Results for individual samples are similar within uncertainty, with pressure differences within individual samples ≤ 0.4 kbar. An exception to this is sample 1-198, with a pressure variation of 1.1 kbar. Bunn pressures range from 1.3 to 3.6 kbar (average = 2.3 kbar), excluding the 4.4 kbar value from BEA-2. This range is similar though slightly greater than that for ED samples. BEA-5 has the highest pressure (3.0-3.6 kbar), and BEA-1 the lowest (1.3-2.1 kbar).

Samples FL-(MC)-10 and CL-6A have slightly greater pressures, averaging 2.7 and 3.4 kbar respectively, although this may be the result of obtaining T and P for only single samples. However, a slightly higher pressure of metamorphism would be consistent with the occurrence of sillimanite (fibrolitic sillimanite) that may occur at or near the and-sill univariant curve. A low value (1.4 kbar) for FL-(MC)-10 was produced from a garnet rim, and is interpreted to represent re-equilibration during uplift. All results are consistent with the P-T zone indicated on the KFMASH petrogenetic grid. Results from all samples plot near the and-sill univariant curve, in agreement with the presence of andalusite and/or sillimanite in all samples.

Metavolcanic Rocks

The grt-hbl geothermometer, based on the Fe-Mg exchange reaction: prp + Fe-hbl = alm + Mg-hbl (Graham and Powell, 1984), was used for metamafic samples FL-(MC)-14 and CL-2A. The grt-hbl-pl-qtz geobarometer (an + Fe-act = grs + alm + Fe-ts + qtz) was also used (calibration of Kohn and Spear, 1990). Additionally, the grt-cpx geothermometer (alm + di = prp + hd) and grt-cpx-pl-qtz geobarometer (di + an = grs + prp + qtz) were used on sample CL-2A, with the calibrations of Powell and Holland (1985, 1988).

Estimates of T and P for sample FL-(MC)-14 are 580°-597°C, and 3.1-3.5 kbar (Table 3b). The temperatures are slightly higher than those for metapelitic sample FL-(MC)-10, though the pressure estimates for the two samples are similar. From the Bunn area, a metabasalt sample (BE-616A) and felsic metavolcanic sample (BE-320A), both containing the assemblage grt + hbl + pl, gave results of 537° and 610°C, and 3.8-3.9 kbar, respectively, comparable with mafic rocks from the other areas, although at a slightly greater pressure.

Clinopyroxene was found only in mafic samples from the Clayton area, and thus only CL-2A was used in grt-cpx thermobarometry. Temperatures obtained from grt-cpx thermometry (538°-578°) are greater than those determined using the grt-hbl thermometer, and more consistent with temperatures from metapelitic sample CL-6A. This suggests that the grt-cpx-pl assemblage may represent peak equilibrium conditions, and hornblende may not belong to the peak assemblage, or that the calibrations used are inappropriate for these rocks. Pressures obtained for this sample (1.9-3.0 kbar) are slightly lower than those obtained for metapelitic samples from this area.

Thermobarometry Summary

These results suggest similar conditions of emplacement for two plutons of the Rolesville batholith. For the Archers Lodge pluton, ED, MC, and CL rocks indicate maximum wall rock temperatures between approximately 540° and 611°C, and pressures between 1.6 and 3.6 kbar (Ganguly and Saxena calibrations). The highest pressures of this range are from the CL area, and the lowest are from the ED area. HC samples may indicate slightly higher temperature and/or pressure for the adjacent side of the Archers Lodge pluton, based on the abundance of sillimanite. BE samples indicate temperatures of 540°-618°C, and pressures of 1.9-3.6 kbar

(Ganguly and Saxena calibrations) for the Bunn pluton. These results fall in a zone between the hornblende hornfels and low pressure amphibolite facies (Yardley, 1989).

DISCUSSION AND POSSIBLE TECTONIC IMPLICATIONS

Results of P-T estimates allow comparison between the Rolesville and other late Paleozoic granitoid plutons. Detailed studies on the Lilesville and Liberty Hill plutons (see Figure 1) have documented development of thermal aureoles in greenschist facies country rocks of the Carolina terrane. Contact metamorphism around the Liberty Hill pluton (Speer, 1981) was considered to be isobaric at approximately 4.5 kbar, at temperatures estimated from 680° to less than 610°C (Speer, 1981). The presence of kfs+crd, and the disappearance of muscovite in the inner aureole of the Liberty Hill, confirm higher temperatures than those determined from this study for the Rolesville country rocks. Emplacement pressure of the Lilesville pluton was estimated at 2.0-3.5 kbar, with temperature estimates obtained from grt-bt thermometry of the exterior Lilesville aureole ranging from 519° to 691°C (Evans and Speer, 1984). Here again the presence of kfs+crd suggests a higher temperature than estimated for the Rolesville batholith.

Pressures of crystallization for several late Paleozoic plutons in the Piedmont were estimated at 2.1-5.1 kbar from aluminum-in-hornblende thermobarometry on rocks of the plutons themselves (Vyhnal and others, 1991). Crystallization pressure for the Castalia pluton, now considered part of the Rolesville batholith, was estimated at 3.0 ± 0.7 kbar, comparable to estimates presented here for the Bunn and Archers Lodge plutons. All three plutons intrude the Spring Hope terrane. Vyhnal and McSween (1990) inferred greater depths of emplacement for plutons in high-grade regional metamorphic belts (Charlotte, Kings Mountain, and Raleigh) than in the lower grade metamorphic belts (Carolina slate belt/Carolina terrane and Eastern slate belt/Spring Hope terrane).

It has been suggested that the rocks of the Raleigh terrane represent the Alleghanian high-grade metamorphic infrastructure beneath the Spring Hope and/or Carolina terranes (Samson and others, 1995; Heller, 1996; Stoddard and others, 1996), possibly separated from those terranes by one or more (pre-Alleghanian) thrust fault(s) (Farrar, 1985b; Carpenter and others, 1995, 1998a,b).

Prior to intrusion of the batholith, the Spring Hope and Carolina terranes were shallower and at a lower metamorphic grade than the Raleigh terrane, but all terranes were strongly overprinted by the Alleghanian metamorphism that occurred synchronously with intrusion of the batholith. However today, deeper wall rocks, belonging to the Raleigh terrane, are exposed along the west and north sides of the batholith, relative to the Spring Hope terrane rocks on the east and south.

Mineral assemblages suitable for thermobarometry have not yet been identified within the Raleigh terrane to allow for quantitative estimates of its crustal depth. However, just west of the Nutbush Creek fault zone, schist of the Crabtree terrane (informally the garnet-kyanite schist of Horse Creek; Horton and others, 1994), contains the assemblage grt + ky + st + bt + ms + pl + qtz (GKS on Figure 2). P-T estimates for these rocks determined by Speer (1994b) are 660°C, 10 kbar for garnet cores, and 645°C, 8 kbar for garnet rims. Speer's analyses (1994b) recast using thermobarometers and calibrations used in this study yield pressure estimates of 5.9 -7.9 kbar (see Table 3a), corresponding to a crustal depth of 22.8-30.5 km.

Although the Crabtree terrane is separated from the Raleigh terrane by the Nutbush Creek fault, the two terranes may represent crustal levels that were similar at the time of emplacement of the Rolesville batholith. This likelihood is suggested by the following argument. First, there is no apparent discontinuity in metamorphic grade across the fault in this area. As shown by Parker (1979), there is a continuous Barrovian-style metamorphic gradient from west to east across northern Wake County, from chlorite zone adjacent to the eastern edge of the Triassic basin to kyanite zone in the Crabtree

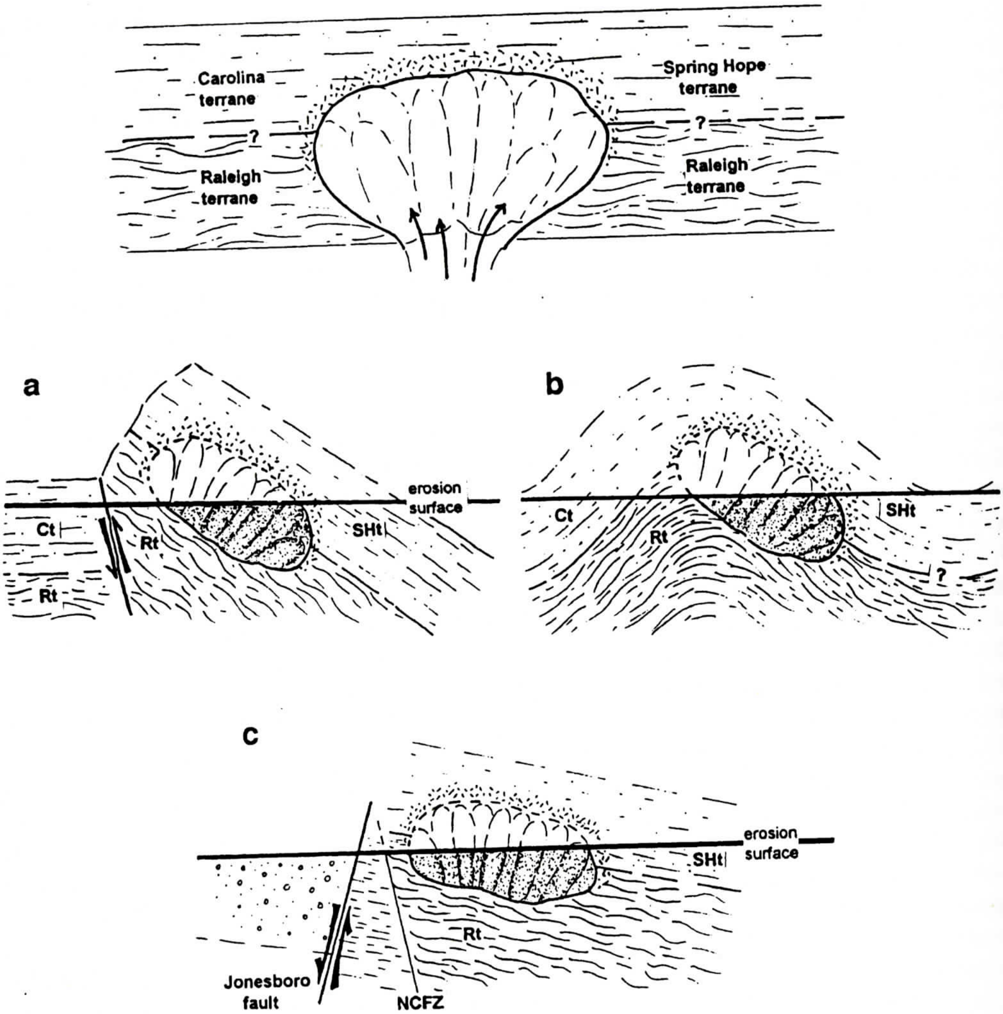


Figure 12. Cartoons depicting possible models for tilting of the Rolesville batholith and the eastern Piedmont. Drawings are schematic. Cross-sections are unbalanced and not to scale. Approximate present erosion surface shown in a, b, and c. Stippling: thermal aureole. Abbreviations: Ct: Carolina terrane; Rt: Raleigh terrane; NCFZ: Nutbush Creek fault; SHt: Spring Hope terrane. Top: Composite batholith intrudes along active shear zone(s) during Late Paleozoic Alleghanian orogeny. Boundary between the Spring Hope/Carolina terrane(s) and Raleigh terrane may be a low angle thrust fault or regional metamorphic gradient. (a) Possible vertical motion along an unknown Alleghanian or younger fault zone. Any such motion may have been overprinted. (b) Possible Alleghanian folding scenario, Rolesville batholith in core of Raleigh antiform. (c) Additional vertical offset resulting from normal motion along Mesozoic Jonesboro fault. Proposed throw on the Jonesboro can account for only a portion of the inferred tilt of the batholith.

terrane. Sparse occurrences of sillimanite zone rocks in the Raleigh terrane (Stoddard, unpublished mapping) represent a logical continuation of this gradient.

Movement along the Nutbush Creek fault must have predated intrusion of the Rolesville batholith, because the granitic rocks do not have a tectonite fabric. In fact, the Falls leucogneiss, which possesses a tectonite fabric and lies within the Nutbush Creek fault zone in this area, is itself recrystallized, overprinted by the same Alleghanian metamorphism which accompanied batholith emplacement and affected the terranes in question. Although there is need for additional isotopic ages to document the timing of metamorphism in the various terranes, existing dates, that can reasonably be inferred to record metamorphism, or cooling from a metamorphic peak, suggest an Alleghanian event (e.g. Russell and others, 1985).

Assuming that metamorphism in the Crabtree and Raleigh terranes was Alleghanian (and synchronous with batholith intrusion and the contact metamorphism described here), then a much deeper level of the Rolesville batholith and its wall rocks is exposed on the west side than on the east and south sides. The different levels exposed today on opposite sides of the Rolesville would then be attributable to post-intrusion crustal movements. One possibility is tilting (or arching) of the batholith and the surrounding region of the eastern Piedmont. Assuming an originally roughly horizontal lower surface (floor) for a mushroom or anvil-shaped Rolesville batholith, the batholith should extend to greater depths on its eastern edge, within the Spring Hope terrane. This concept is supported by gravity studies of the eastern Piedmont (Stephens, 1988; Lawrence and others, 1997) showing an asymmetric gravity profile, with the minimum gravity values occurring at the eastern margin of the batholith.

Several possible models can account for this crustal tilting or uplift of the Raleigh terrane. Similar to the model of Speer and others (1994a), we suggest that the granitoid rocks of the Rolesville batholith were intruded along an active shear zone into the Spring Hope terrane and deeper Raleigh terrane during the Alleghanian orogeny (Figure 12). The intrusion of the granitoid rocks may have been followed by one or more of the following tectonic events, resulting in the present configuration: (1) West of the batholith, a hypothetical fault zone may have had major vertical motion down to the west (Figure 12a); this motion may have been overprinted by documented dextral shear (Druhan and others, 1988, 1994; Horton and others, 1993). (The hypothesized fault zone may have been a precursor to any of several mapped faults in this region, including the Leesville, Falls Lake, Nutbush Creek, and Lake Gordon faults.) (2) Variations in exposed crustal levels may be the result of folding of earlier isothermal surfaces, with the Rolesville batholith emplaced in the core of the Raleigh antiform (12b). (3) Normal motion on the Mesozoic Jonesboro fault (or other Mesozoic faults) can explain some vertical displacement, although this has been estimated to be on the order of only a few km (Reinemund, 1955; Figure 12c).

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The Chrno- and Lithostratigraphic Significance of the Type Section of the Middendorf Formation, Chesterfield County, South Carolina

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ABSTRACT

The name Middendorf Formation has been widely used in the Coastal Plain of South Carolina, eastern Georgia, and southern North Carolina since 1904, despite conflicting interpretations of the age and stratigraphic relations of the unit at its type locality. Between 1995 and 1998, the U.S. Geological Survey, in cooperation with the South Carolina Department of Natural Resources, drilled three continuously cored holes to the south and to the east of the type section of the Middendorf Formation, which is located in Chesterfield County, South Carolina. In addition, two outcrops to the northeast of the type section were sampled for biostratigraphic control. The litho- and biostratigraphic relations of the units in these cores and outcrops provide significant insights into the age of the Middendorf Formation at its type locality, and how this age impacts regional correlations of the formation. A projection of formational contacts and thicknesses from downdip areas into the type locality of the Middendorf Formation indicates that the type section is most likely a facies of either the uppermost Bladen Formation (of the Black Creek Group), or the uppermost Bladen *and* the lowermost part of the Peedee Formations. This report documents the evidence that supports this interpretation. The implication of this interpretation is that the name "Middendorf" has been applied to a variety of units throughout the southeastern United States, all of which display a similar lithology, but differ significantly in stratigraphic position and age. For these reasons, we recommend that the name Middendorf be restricted for use with strata that occur only in the vicinity of the type locality, and use of the name "Middendorf" for units elsewhere in the Coastal Plain be reconsidered.

INTRODUCTION

Currently, the name Middendorf Formation is widely applied in the Coastal Plain of South Carolina, eastern Georgia, and southern North Carolina to crossbedded kaolinitic clayey sands of Late Cretaceous age. The term Middendorf "phase" was first proposed by Sloan (1904) to differentiate these deposits from his underlying Hamburg "phase," which Sloan (1904) considered the oldest outcropping Cretaceous formation in South Carolina. Subsequent workers described the Middendorf elsewhere as overlying the Cape Fear Formation of Stephenson (1907). In addition, beds once assigned to the "Tuscaloosa" Formation by Cooke (1936) have largely been reassigned to the Middendorf by subsequent workers.

Sloan (1904) did not establish a type section

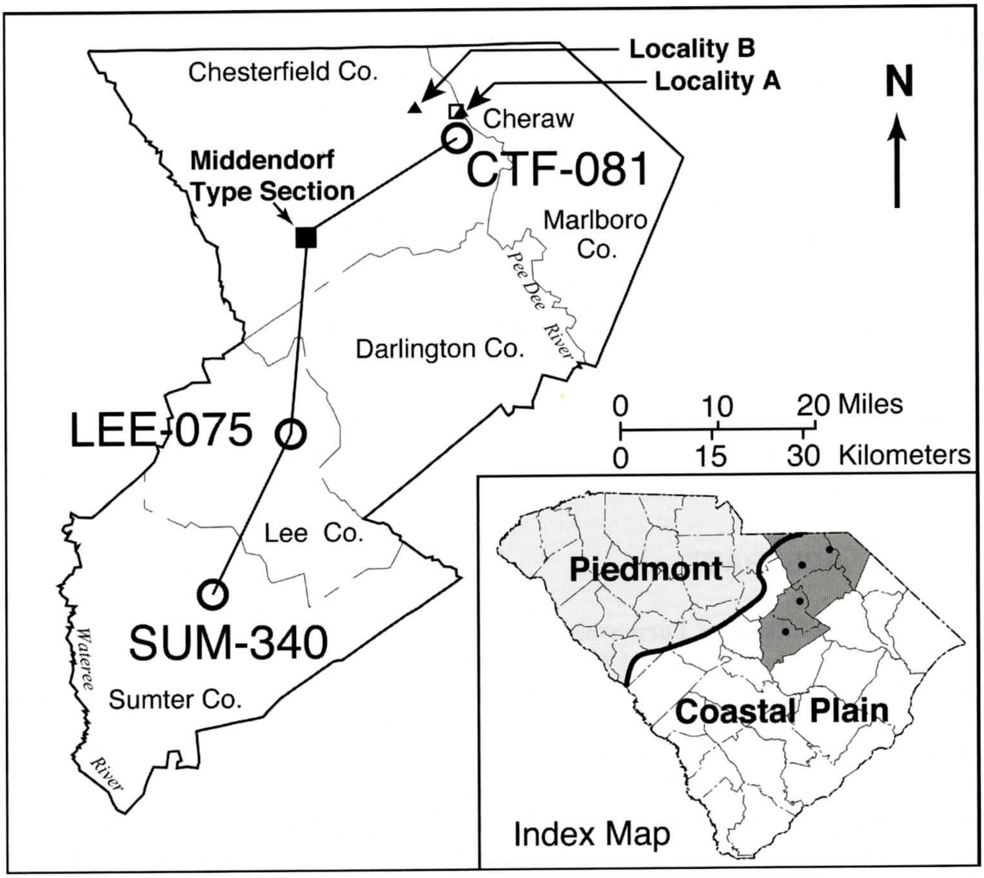

Figure 1. Location of the type section of the Middendorf Formation, Chesterfield County, South Carolina as well as nearby USGS core holes (CTF-081, LEE-075, SUM-340) and outcrop sample sites (Locality A and B). Also shown is the line of section for Figure 4.

for the Middendorf, although Berry (1914), Cooke (1926, 1936), and others considered an exposure along the Seaboard Coast Line Railroad, approximately 2 miles northeast of the community of Middendorf in Chesterfield County, South Carolina, as the type section (Fig. 1; see also, Sloan, 1904, p. 108). Heron (1958a) and Swift and Heron (1969), documented the presence of three distinct lithologic units at the type section, but the association between these units and Sloan's Middendorf Formation was never established.

As with many updip Coastal Plain outcrops, the type section at Middendorf is highly weathered and is only sparsely fossiliferous. Leaf impressions were studied by Berry (1914), who interpreted the Middendorf as correlative with the Black Creek Formation. Cooke (1936) discounted the paleobotanical evidence of Berry (1914) as he considered the inconsistencies in Berry's collections to outweigh any similarities between the Middendorf leaf impressions and those from the Black Creek Formation (now Black Creek Group). The scarcity of fossil leaves elsewhere in the Coastal Plain hampered regional correlation and consequently, Cook (1936) proposed abandoning the name Middendorf in favor of the Tuscaloosa Formation. Dorf (1952) also studied the leaves at the type section and agreed with Berry that the strata are chronostratigraphically equivalent to the Black Creek.

The name Middendorf was resurrected in South Carolina by Swift and Heron (1969) and subsequent workers have applied the name regionally to other units based on their lithologic similarities and their stratigraphic position above the Cape Fear Formation. However, the stratigraphic relations implied by using the name Middendorf in this manner lacked the benefit of mappable correlations or paleontological support that would demonstrate a consistent and unique stratigraphic position (for example, Swift and Heron, 1969; Woollen and Colquhoun, 1977; Colquhoun and others, 1983; Gohn and others, 1977; Prowell, 1994b; Campbell and Gohn, 1994; Fallaw and Price, 1995). Recent studies by Prowell and Christopher (2000a, 2000b) and Christopher and others (2000) indicate that the majority of units assigned to the Middendorf Formation throughout the southeast do not occupy a unique and consistent stratigraphic position, nor are they necessarily correlative with each other. Inasmuch as Article 22 of the North American Stratigraphic Code (NASC; North American Commission on Stratigraphic Nomenclature, 1983) requires that a formation be defined, in part, by its stratigraphic position, and Article 24d requires that it must be mappable, it appears that the Middendorf Formation is in violation of both articles.

In addition, pollen data have shown that strata assigned to the Middendorf Formation range in age from Coniacian to Maastrichtian (Christopher and others, 2000; Christopher, 2000). In South Carolina, downdip marine strata of this age range contain numerous regional unconformities, many of which have been recognized in the updip fluvial facies (Christopher and Prowell, in press). Although Article 22 of the NASC states that a formation is defined independently of its geologic history, age, and biostratigraphic considerations, Article 22e recommends against establishing a formation that straddles regional disconformities. Therefore, because the Middendorf Formation has been applied to a repeating sequence of lithologically similar nonmarine facies that are equivalent to a downdip marine section which consists of several distinct and unique formations, and which includes several regional unconformities, it appears that use of the term "Middendorf Formation" as a formal lithostratigraphic unit may be inappropriate, as it is in violation of several articles of the NASC.

Because a formation's type locality serves as the standard by which it is defined and recognized (Article 8, NASC), we undertook a study of the type locality of the Middendorf Formation in an attempt to clarify some of the issues related to its use as a formal lithostratigraphic unit. In addition, we attempted to place the type locality into the local stratigraphic framework. The results of these efforts are documented in this report, and lead us to recommend that (1) the name Middendorf Formation be applied only to units in the vicinity of the type locality, and (2) units referred to as "Middendorf" elsewhere in the Coastal Plain be renamed.

PREVIOUS WORK

Sloan (1904, 1907, and 1908) was the first to discuss the Seaboard Coast Line Railroad section that now serves as the type section of the Middendorf Formation, but he did so only in terms of its association with the economic value of local clay deposits. Berry (1914) placed Sloan's informal units into a chronostratigraphic framework on the basis of paleobotanical data from the upper part of the type section. Berry (1914) recovered 41 species of leaves (preserved as impressions) from these beds, and he noted their similarity to suites of leaves from the Upper Cretaceous (Campanian) Black Creek Formation of Stephenson (1907, 1912). Based on this similarity, Berry suggested that the Middendorf was a phase (or facies) of the Black Creek Formation (now Black Creek Group). Cooke (1926) adopted the name Middendorf, but later discarded it in favor of the Tuscaloosa Formation because he interpreted the units as occupying the same stratigraphic position; that is, he considered both to occur at the base of the Upper Cretaceous depositional sequence and immediately overlie pre-Cretaceous rock (Cooke, 1936). Stephenson and others (1942) agreed with the findings of Berry (1914) and favored the name Middendorf over Tuscaloosa, whose type section is in western Alabama. Dorf (1952) also studied leaf fossils from the Middendorf type section, and his conclusions supported Berry's supposition that the type Middendorf is a facies of the Black Creek Formation.

Heron (1958a, 1958b, 1960), Johnson (1961), Heron and Wheeler (1964) and Heron and others (1965) described the Middendorf as a unique depositional unit that is in facies relationship with their Black Creek (now Black Creek Group) and Peedee Formations. Swift and Heron (1969) re-instated the name Middendorf as a lithostratigraphic unit that is situated above the Cape Fear Formation. These workers also documented the presence of the Middendorf Formation in updip areas of the innermost Coastal Plain and on interfluves between major drainages such as the Pee Dee and Cape Fear Rivers.

Heron and Wheeler (1964) and Swift and Heron (1969) noted the absence of the Middendorf on the Cape Fear River in North Carolina (milepost 101; see Stephenson, 1907), where carbonaceous and lignitic clays of the Black Creek Formation (now Black Creek Group) immediately overlie the poorly sorted, kaolinitic, indurated sand and gravel of the Cape Fear Formation. They also noted that this absence supports the interpretation of Berry (1914) and Dorf (1952) that the Middendorf is a facies of the Black Creek. In this regard, it is important to note that in all other North Carolina river valleys where the top of the Cape Fear is exposed, clays of the Black Creek Group also directly overlie the Cape Fear Formation (N. F. Sohl, oral commun., 1990). Hence, the presence of the Middendorf only in selected topographic settings is a significant observation regarding its stratigraphic position and relation with other units.

Woollen and Colquhoun (1977) and Woollen (1978) drilled numerous auger holes in Chesterfield County, S.C., in an attempt to differentiate Middendorf from Black Creek strata, but the lack of age control inhibited their ability to establish reliable stratigraphic relations, which resulted in numerous miscorrelation. Prowell and Christopher (2000a) and Christopher and others (2000) described how miscorrelation is, historically, the result of a strictly lithostratigraphic application of the name Middendorf to a variety of Upper Cretaceous depositional events, and they demonstrated that the name Middendorf is commonly applied to any unconsolidated, poorly sorted, kaolinitic sand that overlies the Cape Fear Formation, without regard to the age, relation to regional unconformities, or relation to the type locality.

THE TYPE SECTION OF THE MIDDENDORF FORMATION

The type section of the Middendorf Formation is the McKennon railroad stop exposure located approximately two miles east of the community of Middendorf, Chesterfield County, South Carolina. The most detailed description of this type section is in a Ph.D. dissertation by Heron (1958a). An excellent photograph of the exposure was made by L.W. Stephenson and published by Cooke (1936, his plate 11). A later generalized diagrammatic depiction of the exposure was published by Swift and Heron (1969, their figure 11) and Woolen and Colquhoun (1977, their figure 1).

The exposure described by Heron (1958a), Swift and Heron (1969), and Woolen and Colquhoun (1977) occurs on either side of the highway bridge that spans the railroad cut at the McKennon exposure. At the time we visited the outcrop (May, 1998) it was slumped and overgrown, and the stratigraphic relations discussed by these and previous workers were, for the most part, obscured. For this reason, a portion of the railroad cut approximately 200 ft northeast of the highway bridge was cleared of vegetation and the face was smoothed with shovels to expose the lower two-thirds of the outcrop (Fig. 2). The elevation of the land surface at this exposure is +380 ft, although nearby hills reach elevations of +450 ft. The elevation at the cleared exposure was determined by leveling from a benchmark near the highway bridge. The face of the exposure slopes 45^{O} and it was measured and described in detail. In addition, scintillometer measurements were taken every 0.5 ft over the exposure to provide a synthetic gamma-ray profile of the section. The lithologic log and gamma-ray data were combined into a

Figure 2. Photograph of the cleared exposure (1997) at the type section of the Middendorf Formation, McKennon railroad cut, Middendorf, South Carolina (see Figure 3 for vertical scale reference). Footages shown are true vertical distances above the base of the section with their corresponding elevations above sea level indicated in parentheses.

graphic representation of the type section (Fig. 3), where distances measured along the face of the exposure are corrected to true vertical elevation.

The newly exposed and measured section contains three stratigraphic units. The lower unit (0 to 7.3 ft on Figure 3) is characterized by coarse-grained, cross-bedded, clayey sand, the middle unit by laminated fine-grained sand and clay, and the upper unit by massive clayey sand that contains an organic-rich layer at the top of the exposure. This stratigraphic sequence supports the observations of Heron (1958a) and Swift and Heron (1969). The middle stratigraphic unit in the newly measured section appears to be correlative to Unit 2 of Heron (1958a) located near the highway bridge over the railroad (personal comm., S. D. Heron, 2003). Heron's Unit 2 is the most likely candidate for the leaf locality reported by Berry (1914).

The lower stratigraphic unit at the measured section consists of fine- to very coarse-grained, poorly sorted quartz sand. This sand contains

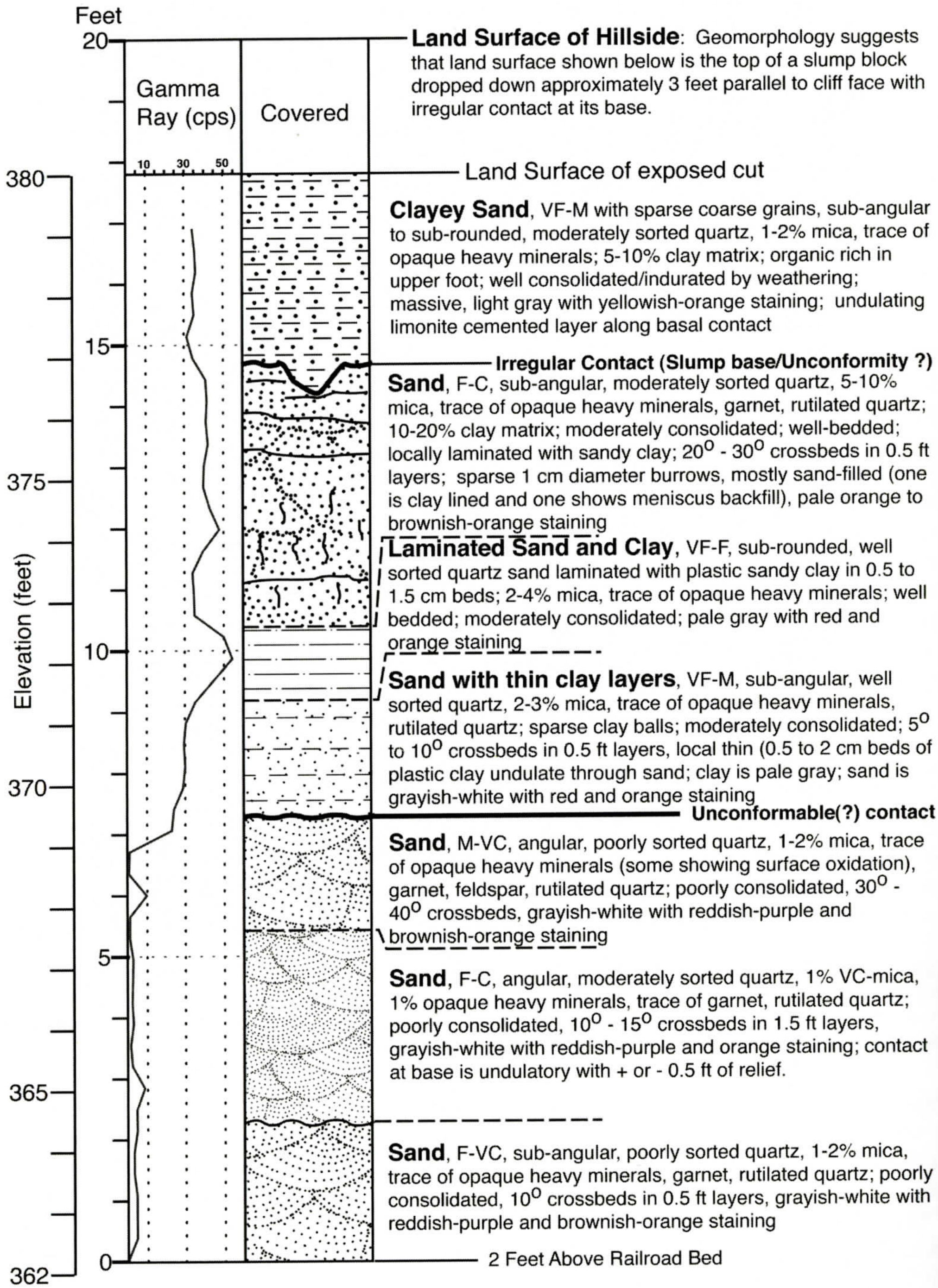

Figure 3. Measured section at the new exposure at the type locality of the Middendorf Formation, McKennon Railroad Cut, Middendorf, S.C.

Table 1. Pertinent data from the USGS core holes and outcrop localities in South Carolina used in this study.

Hole Number/ Outcrop ID	County	Year of Data Acquisition	North Latitude	West Longitude	Elevation of Land Surface (ft)	Total Depth (ft)	Depth to pre-Cretaceous Basement (ft)	Elevation of pre-Cretaceous Basement (ft)	Basement Rock Type	Age of Basement Rock
CTF-081	Chesterfield	1995	34° 38' 35"	79° 54' 42"	193	244	219	-26	phyllite	Paleozoic
LEE-075	Lee	1996	34° 12' 09"	80° 10' 28"	199	554	537	-338	phyllite	Paleozoic
SUM-340	Sumter	1999	33° 59' 25"	80° 21' 32"	180	690	641	-461	redbeds	Triassic
Type section	Chesterfield	1997	34° 32' 59"	80° 07' 48"	390	n/a	~390[1]	~sea level[1]	?	?
Fig. 1, Loc. A	Chesterfield	1978	34° 42' 15"	79° 52' 53"	120	n/a	~90[1]	~30[1]	phyllite	Paleozoic
Fig. 1, Loc. B	Chesterfield	1979	34° 42' 50"	79° 59' 11"	180	n/a	~20[1]	~160[1]	phyllite	Paleozoic

[1]Based on the structure contour map of pre-Cretaceous Basement by Wait and Davis (1986)

trough crossbeds in 2–3 ft sets that dip as steeply as 40°. The lithologic characteristics and sedimentary structures of this unit indicate a fluvial origin, as was proposed by Heron (1958a), Swift and Heron (1969), and Woollen and Colquhoun (1977). An abrupt contact separates this basal sand from the overlying middle unit (7.3 to 14.7 ft on Figure 3) that consists of well sorted, laminated, fine-grained sand and clay. At 10.4 ft above the base of the section, the laminated sand and clay grades into moderately sorted, fine- to coarse-grained clayey sand which is locally interbedded with undulating, laterally continuous laminae of sandy clay. These interbedded clayey sands and laminated sandy clays extend upsection from 10.4 to 14.7 ft. This unit also contains common clay-lined and backfilled burrows that measure approximately 0.5 inch in diameter. In conjunction with the thin undulating clay laminae, the burrows are evidence of a shallow marine (estuarine?) depositional environment. A limonite-stained, irregular contact at 14.7 ft separates the burrowed sand from the upper massive clayey sand (14.7 to 17.8 ft on Figure 3). The upper unit is highly oxidized and weathered, has a mottled texture, and lacks well-defined bedding. When coupled with the presence of an uppermost organic-rich zone, the unit is interpreted as colluvium and (or) residuum on which a soil profile has developed. As the uppermost unit is herein considered post-Cretaceous in age and is poorly exposed, the remainder of this report is focused on the two underlying units.

The lithologic characteristics of the units exposed at this outcrop suggest an abrupt change at 7.3 ft from fluvial conditions below to shallow marine conditions above. This abrupt change at 7.3 ft is also suggested by the scintillometer data which show the lower (fluvial) unit to be a zone of low radioactivity, whereas the overlying (marine) deposit has a higher but more erratic signature. Consequently, we interpret the contact at 7.3 ft as an unconformity, which divides the type section of the Middendorf Formation into two distinct depositional units. The contact between these two units can be seen on Stephenson's photograph of the exposure that was published by Cooke (1936, his plate 11), but Cooke did not restrict the Middendorf to one or the other of these units.

STRATIGRAPHIC FRAMEWORK IN THE VICINITY OF THE MIDDENDORF TYPE SECTION

Between 1995 and 1998, the U.S. Geological Survey, in cooperation with the S.C. Department of Natural Resources, continuously cored three drill holes to pre-Cretaceous rock in the region surrounding the type section of the Middendorf (Fig. 1). In addition, carbonaceous clays collected in 1978 from two local outcrops were analyzed for palynomorphs in order to provide biostratigraphic control (Fig. 1, localities A and B). Pertinent data regarding these localities are presented in Table 1. These cores and outcrop samples provide a solid foundation for establishing the stratigraphic framework in the area around the type locality of the Middendorf Formation, and for incorporating the type locality into this framework.

Collectively, the CTF-081, LEE-075, and SUM-340 wells penetrated at least six Upper Cretaceous formations and one Quaternary (?) formation. Carbonaceous clay samples were recovered from all of the cores and examination of palynomorphs from these samples provides the biostratigraphic control used to correlate the wells and interpret depositional environments. In addition, the two outcrop samples establish the age of the outcropping strata northeast of the type locality, which had been mapped as the Middendorf Formation (Woollen and Colquhoun, 1977) and as the Tuscaloosa Formation (Cooke, 1936; Siple and others, 1956).

A structure contour map of the top of pre-Cretaceous rock in the Carolinas was published by Wait and Davis (1986) and this map was used to determine the relative stratigraphic position of the outcrop sample localities (Fig. 1, localities A and B). A comparison of the elevation of the top of pre-Cretaceous rock at the outcrop sample localities with the Middendorf type locality reveals that the two outcrop localities are updip of, but stratigraphically below, the level of the Middendorf type locality. In fact, both of the outcrop sample localities are low in the stratigraphic section with one (locality B of Fig. 1 and Table 1) being immediately above pre-Cretaceous rock. Pollen from both of these localities can be assigned to the *Sohlipollis* Zone of Coniacian-Santonian age (see Christopher and others, 1999); therefore the oldest Cretaceous strata in the region are Coniacian to Santonian in age.

The regional slope of the pre-Cretaceous rock surface indicates that the Chesterfield (CTF)-081 core hole is approximately on strike with the Middendorf type locality. The other two wells included in the study, Lee (LEE)-075 and Sumter (SUM)-340, are downdip of the type locality. The following formational descriptions were derived largely from the 3 core holes included in this study.

Cape Fear Formation

The basal Cretaceous formation in CTF-081, LEE-075, and SUM-340 and in the outcrop belt around Cheraw, South Carolina (Fig. 1, localities A and B), is the Cape Fear Formation. The Cape Fear was originally described by Stephenson (1907) and the name is in use in both North and South Carolina thanks to Heron and others (1968) and Sohl, (1976). The Cape Fear at our study sites is characterized by poorly sorted, angular, fine- to very coarse-grained arkosic quartz sand and gravel in a sticky light olive gray (5Y6/1) clay matrix. The formation in our core holes consists of 5 to 10 fining-upward sedimentary sequences that generally begin with gravelly sand at the base and terminate in sandy clay. In the uppermost parts of each of these sequences, post-depositional weathering has altered the sticky clay matrix and overprinted the primary color with pastel hues. The Cape Fear is generally characterized by its dense and weakly silica-cemented nature, which produce low resistivity readings on electric logs. However, in highly weathered situations, the Cape Fear loses its dense and cemented nature, and in these settings it is a white, poorly consolidated, crossbedded clayey sand. Such changes may be responsible for some of the miscorrelations in the outcropping Upper Cretaceous strata of the Carolinas.

The absence of dinoflagellates is suggestive of a non-marine depositional environment. Similarly, the presence of fining upwards sequences from arkosic gravelly sand to clay are indicative of point bar deposits in a fluvial depositional environment. Both of these observations suggest that in this region, the Cape Fear Formation was deposited in a non-marine environment, most likely in an upper delta plain setting. Interestingly, Siple and others (1956) reported a diverse foraminiferal suite and Heron (written communication, 2002) reported burrows at our Locality A (Fig. 1), but our observations and pollen samples from this outcrop failed to reveal any evidence of marine conditions. Carbonaceous clay samples from the Cape Fear Formation in all three core holes and both outcrop samples (Fig. 1, localities A and B) were examined for palynomorphs, specifically, terrestrial pollen and marine dinoflagellates. No dinoflagellates were found in any of the samples. Included in the pollen assemblages are *Sohlipollis capefearensis, S. delicatus*, and *S. robustus*, all of which are markers for the late Coniacian to late Santonian *Sohlipollis* Zone of Christopher and others (1999). The *Sohlipollis* Zone is equivalent biostratigraphically to calcareous nannofossil Zones CC12 (upper part) through CC17 (lower part), and the Cape Fear Formation most likely includes the Turonian to Coniacian Stages (i.e., calcareous nannofossil Zones CC12 and the lower part of CC13).

Black Creek Group

Unconformably overlying the Cape Fear in all three cores is the Black Creek Group, which consists of three formations. In ascending stratigraphic order, these formations are the Tar Heel, Bladen, and Donoho Creek Formations of Campanian (Upper Cretaceous) age (see Owens, 1989; Sohl and Owens, 1991). Although these formations were defined from exposures along the Cape Fear River in North Carolina, their correlatives in eastern South Carolina can be identified palynologically (Christopher and others, 1979; Sohl and Christopher, 1983).

Tar Heel Formation

The Tar Heel Formation was deposited unconformably above the Cape Fear Formation and consists of thick layers of poorly sorted, angular, clayey, fine- to very coarse-grained quartz sand interlayered with thick beds of plastic, sandy, silty kaolinitic clay. Individual sand beds are up to a few feet thick and contain moderately dipping crossbeds. Locally, the sands are well sorted and contain thin silty clay beds suggestive of marine influence during deposition. The entire Tar Heel Formation is characterized by carbonaceous debris, especially in the clay-rich beds. A thick layer of clay composes the upper part of the formation in SUM-340 and LEE-75. This clay layer has desiccation cracks and root structures in its upper surface which indicate sub-aerial exposure prior to the deposition of the Bladen.

Pollen assemblages from this unit indicate that the age of the Tar Heel is the early, but not earliest, Campanian. Dinoflagellate abundance and depositional indicators suggest that the Tar Heel in the SUM-340 area was deposited in open marine conditions, whereas at the LEE-075 well, deposition was marginal to restricted marine with a strong fluvial influence. North of the LEE-075 well, deposition is most likely fluvial.

Bladen Formation

The Bladen Formation unconformably overlies the Tar Heel Formation. The base of the formation is marked by a coarse erosional lag deposit characterized by quartz gravel and unweathered feldspar. The bulk of the Bladen consists of fine- to very coarse-grained quartz sand with sparse gravel that fines upward into very fine- to medium-grained clayey quartz sand. The coarser-grained beds in the basal part of the formation are poorly sorted, crossbedded, and contain common lignite and pyritized lignite. The finer-grained sand beds higher in the unit are characterized by a higher percentage of clay that occurs in thin undulatory (flaser bed) carbonaceous lenses. In the vicinity of the SUM-340 well, the sand beds within the Bladen Formation are finer-grained, clay-lined burrows are present, low angle crossbeds are common, and a thick, plastic carbonaceous clay bed characterizes the uppermost part of the formation. The flaser beds and clay-lined burrows suggest a shallow marine depositional environment in the SUM-340 area, but the coarser-grained sand and gravel in the lower part of the formation in LEE-075 suggests a fluvial environment overlain by transgressive marine deposits.

Pollen assemblages from the Bladen Formation in the South Carolina cores correlate with those from the Bladen Formation as mapped by Owens (1989) and Sohl and Owens (1991) on the Cape Fear River. Based on this correlation, the age of the Bladen Formation is in the middle part of the Campanian. The distribution of dinoflagellates in the palynomorph samples in conjunction with the sedimentary features in the formation supports the interpretation of a fluvial environment overlapped by a shallow marine depositional environment.

Donoho Creek Formation

The Donoho Creek Formation was deposited unconformably above the Bladen Formation, and it consists of fine- to very coarse-grained clayey quartz sand fining upwards into fine- to very fine-grained sand and silty clay. The formation is largely sand in the lower part and approximately equal parts of sand and clay in the upper part. The coarser-grained sands in the lower part are crossbedded, whereas the sands in the upper part are planar and typically laminated with thin carbonaceous silty clay layers. Large lignite clasts and abundant mica are common. The Donoho Creek Formation in LEE-075 is only 9 ft thick and its lithology corresponds to the clayey fine-grained sand that characterizes the upper part of the formation in the SUM-340 core. The bed forms suggest a shallow marine depositional environment, although the coarser-grained sand in the lower part of the formation in SUM-340 suggests an earlier restricted marine environment followed by deepening marine conditions.

The pollen assemblages from this unit correlate with the Donoho Creek Formation mapped by Owens and Sohl (1989) and Sohl and Owens (1991) on the Cape Fear River. Based on this correlation, the Donoho Creek is assigned to the upper Campanian. The presence of dinoflagellates in the palynomorph samples supports the interpretation of a shallow marine depositional environment.

Peedee Formation

The Peedee Formation unconformably overlies the Donoho Creek Formation. It was originally viewed as a single open marine deposit (Stephenson, 1912, 1923) but some subsequent authors suggested that it might contain several episodes of sedimentation (Swift and others, 1969; Sohl and Christopher, 1983; Prowell, 1994a). Recent studies by Christopher (2000), Bridges and others (2001), and Christopher and Prowell (in press) indicate that the Peedee Formation is actually composed of three depositional events related to fluctuations of sea level. These fluctuations have resulted in unconformable contacts within the Peedee that can be traced throughout South Carolina and into neighboring regions of North Carolina and Georgia. The depositional environment for each of these events is so similar that previous investigators did not recognize the true stratigraphic relations. Moreover, the non-marine facies of these Peedee units (i.e., the Steel Creek Formation of Fallaw and Price, 1995, and the Sawdust Landing Formation of Muthig and Colquhoun, 1988; Frederiksen, 2000), are also present in updip areas of the Coastal Plain. Only the lowermost 2 units of the Peedee are *exposed in the study area* and are hereafter informally called the lower and middle Peedee units.

Lower Peedee Unit

The lower Peedee unit is composed of a bed of fine- to very coarse-grained sand which grades rapidly upward into very fine- to fine-grained, well sorted sand with local thin beds of quartz gravel. Its basal contact is marked by a bed of very coarse-grained sand and well-rounded quartz gravel. Clay-lined burrows were observed in the less-clayey sand but the extent of burrowing is difficult to judge because of the small diameter of the core. The well sorted sand commonly contains interlayered beds of lignitic interlayered sand and clay that collectively measure several feet in thickness. The thin clay layers in these beds have an undulatory (flaser bed) appearance.

Palynomorph assemblages from the lower Peedee unit in SUM-340 are of late Maastrichtian age (Christopher, 2000; Christopher and Prowell, in press). The presence of dinoflagellates in these samples in conjunction with the observation of burrows and flaser bedding suggests a near shore, marginal marine environment of deposition.

Middle Peedee Unit

The middle unit of the Peedee Formation is composed of beds of fine- to coarse-grained, poorly sorted sand alternating with beds of laminated very fine- to fine-grained sand and clay. Its basal contact is marked by a bed of very coarse-grained sand and well-rounded quartz gravel several feet thick. The coarser-grained sand beds are more common updip in the LEE-075 well, where they contain sparse to common quartz pebbles. The laminated sand and clay beds are very carbonaceous and highly micaceous, and concentrations of lignite accentuate low-angle crossbedding. The laminated sand and clay beds have undulatory bed forms suggestive of flaser bedding.

The palynomorph assemblage in SUM-340 from the middle unit of the Peedee Formation suggests a middle late Maastrichtian age (Christopher, 2000; Christopher and Prowell, in press). The presence of dinoflagellates in this sample in conjunction with the flaser beds, the crossbedding, and gravelly sand beds is suggestive of a fluvial-marine interface in a marginal marine environment.

Post-Cretaceous (undifferentiated)

Beds of fine- to very coarse-grained clayey sand and sandy clay, beds of very fine- to fine-grained, well sorted sand, and beds of laminated fine-grained sand and clay unconformably overlie the Cretaceous beds in LEE-075 and SUM-340. The basal contact is marked by a bed of very coarse-grained sand and well-rounded quartz gravel that is less than a foot thick. The overlying laminated sand and clay beds are highly micaceous and contain evidence of oxidized lignitic matter. Slight lithologic differences accentuate low angle crossbedding. Small (0.25 inch) diameter worm(?) burrows were also observed. Above the laminated sand and clay beds are thick beds of fine- to very coarse-grained clayey sand. In SUM-340, the clayey sand is poorly to moderately sorted and contains large (0.5 inch diameter) clay-lined burrows. The correlative sand in LEE-075 is coarser-grained, more poorly sorted, and lacks marine fossils. A thick bed of sandy clay forms the top of the section in LEE-075. The sparse sedimentological evidence suggests that the post-Cretaceous strata at SUM-340 were deposited in an estuarine environment that grades upwards into a more fluvial environment. These deposits have been considered Quaternary by most previous workers.

Nine feet of loose, moderately sorted sand is present in CTF-081 but it contains no clay and no sedimentary structures (Prowell and Christopher, 2000b). This sand is not shown on the diagrams in this report because local outcrops *suggest* that it was deposited in an eolian environment as a dune in the Carolina Sand Hills.

No diagnostic fossils were recovered from any of these post-Cretaceous units, and their stratigraphic interrelations are unknown. In this report, we have combined them under the heading "Post-Cretaceous (undifferentiated)" as they have no relevance to the age, depositional environment, or correlation of the Cretaceous units at the type locality of the Middendorf Formation.

STRATIGRAPHIC INTERPRETATION OF THE MIDDENDORF TYPE SECTION

The CTF-081, LEE-075, SUM-340 wells, together with a hypothetical well at the Middendorf type section were used to construct a cross section (Fig. 4) in order to relate the units exposed at the type section with those in the coreholes. The cross section was referenced to sea level and the elevation at each well head was used to define the land surface between wells, although local topography may be somewhat greater.

The hypothetical well at the type section was

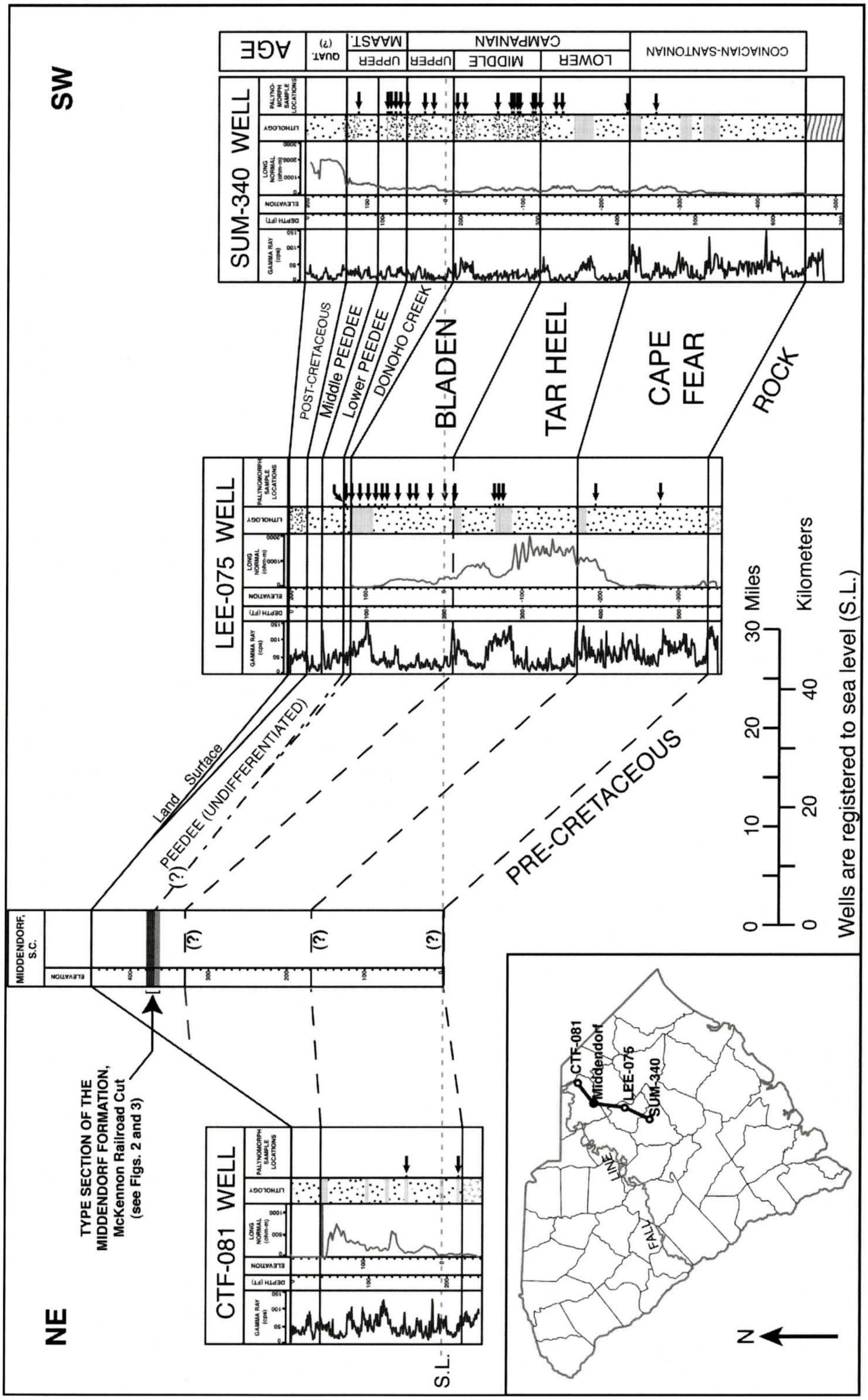

Figure 4. Geologic cross section through the Middendorf type area, eastern South Carolina.

constructed with reference to 1:24,000 topographic data and the pre-Cretaceous "basement" rock map of Wait and Davis (1986). The land surface elevation of the hypothetical well in the vicinity of the Middendorf type locality comes from the Middendorf 1:24,000 topographic map, which indicates that the maximum elevation in the area to be approximately +450 ft. The bottom of the hypothetical well was determined from the structure contour map of pre-Cretaceous rocks by Wait and Davis (1986). Their map places the top of Paleozoic rock at approximately sea level. An alidade survey from a local benchmark (+390 ft) indicates that the elevation of the newly exposed portion of the type section (Figs. 2 and 3) is +362.2 ft at the base and +380.0 ft at the top of the exposure. The core descriptions and palynological analyses discussed previously were used to define the formations shown on the cross section (Fig. 4). The unconformities that separate these formations were correlated between the cored wells and extrapolated through the type area of the Middendorf. The resulting stratigraphic framework in the Middendorf type area allows for placement of the type section in the regional stratigraphic framework.

One of the more obvious features on figure 4 is that the elevation of the Middendorf type section is significantly higher than most of the strata in the surrounding wells. This difference in elevation suggests that the Middendorf type section is probably not the equivalent of the Cretaceous formations in the lower part of the surrounding wells. For example, when the thickness of the combined Cape Fear and Tar Heel Formations in the LEE-075 well is projected updip to the Middendorf type section as a uniformly thick section whose upper surface parallels the pre-Cretaceous basement, the base of the exposure at the type section is more than 30 ft higher than the top of the Tar Heel. Therefore, the relations depicted on the cross section suggests that the type section is stratigraphically equivalent to one or more of the formations that post-date the Tar Heel. In other words, it is equivalent to some part of the Bladen, Donoho Creek, and (or) Peedee Formations.

Correlating the Middendorf type section with specific post-Tar Heel formations is dependent, in large part, on the interpretation of the contact between the two Cretaceous units exposed in the type section. If, as we suspect, the contact between these units is an unconformity, the most likely stratigraphic equivalent for the lower fluvial unit is the Bladen Formation, which would have changed facies from that of a marginal marine environment at the LEE-075 well to that of a fluvial environment at the Middendorf type section. The Donoho Creek Formation thins to 9 ft in the LEE-075 well, and unless this thinning is the result of local events (for example, cut-and-fill), the formation is not likely to be present at the Middendorf type section. The upper marine unit at the type section is probably equivalent to one of the Peedee units, as marine conditions are reflected in the Peedee in both the SUM-340 and LEE-075 cores. However, the contact between the fluvial and marine units at the type section could also represent an intertonguing of marine and non-marine depositional environments that are part of a single genetic unit. In this scenario, both the fluvial and marine units would likely be facies of the Bladen Formation.

The differences in stratigraphic relations that result from the different interpretations of the contact at the type section of the Middendorf Formation are significant. If the contact is unconformable, then the type section of the Middendorf Formation contains a Campanian fluvial unit overlain by a Maastrichtian marine unit. If the contact reflects intertonguing, then the entire type section is Campanian. However, both interpretations illustrate that the type section of the Middendorf Formation does not occupy a unique stratigraphic position, and that the Cretaceous units exposed at the type locality are of an age that is considerably younger than that traditionally assigned to the Middendorf Formation elsewhere in the Coastal Plain.

REGIONAL IMPLICATIONS

Assignment of the name Middendorf to strata not in the vicinity of the type section has been based on either lithologic similarity and (or) presumed stratigraphic position. Traditional

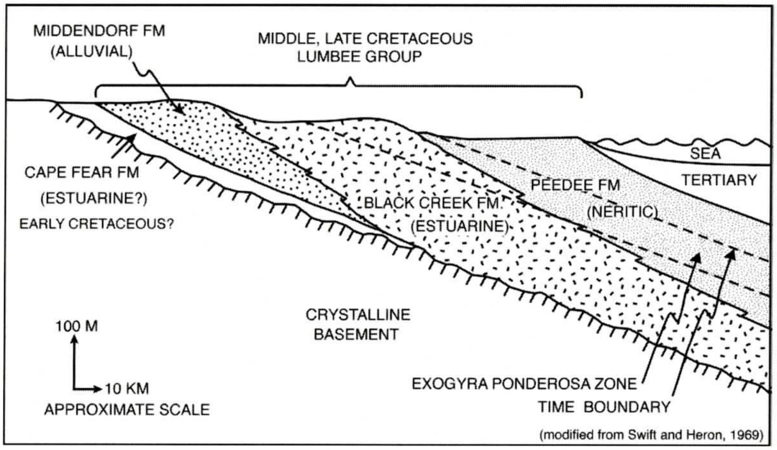

Figure 5. Traditional concept of Cretaceous deposition and facies relations in the Carolinas showing the relative stratigraphic position of the Middendorf Formation (modified from Swift and Heron, 1969).

Cretaceous stratigraphy in the Carolinas held that four extensive formations were deposited in a progressive onlap sequence. This idea was popularized in illustrations by Brett and Wheeler (1961), Swift and Heron (1969), and Swift and others, (1969) (see Fig. 5). Their concept was that the estuarine(?) Cape Fear Formation was deposited during the Early Cretaceous, and eventually the Middendorf (fluvial), Black Creek (deltaic), and Peedee (marine) Formations were deposited unconformably above the Cape Fear during a single Late Cretaceous transgression. According to this interpretation, the geologic history of the Cape Fear is independent from that of the Middendorf, Black Creek, and Peedee Formations. In their view, all of the Upper Cretaceous formations occur in facies relationship, and for stratigraphic purposes, any unconsolidated, crossbedded kaolinitic sand immediately above the Cape Fear Formation was assigned to the Middendorf Formation. However, in their interpretation of regional deposition, they failed to note, or attached little significance to the numerous unconformities throughout the Cretaceous sequence, which are critical elements in more recent stratigraphic interpretations (Sohl and Owens, 1991; Christopher and others, 2000; Prowell and Christopher, 2000a).

Because the "Middendorf" strata are largely non-marine, the misapplication of the name Middendorf was not recognized until the development of a palynological zonation for the southeastern U.S. (Christopher and others, 1999; Christopher and Prowell, in press). With more extensive information, Christopher and others (2000) concluded that sections of strata referred to as Middendorf by previous authors ranges from Coniacian to Maastrichtian in age, and in general these sections are not correlative because of significant differences in their age. Throughout most of the Carolinas and Georgia, the bulk of the sediment referred to the Middendorf Formation is Coniacian to lower Campanian in age (for example, Gohn, 1992; Gohn and Campbell, 1992; Prowell, 1994b; Van Pelt and others, 2000). In the northwestern part of the South Carolina Coastal Plain and adjacent parts of Georgia, the "Middendorf" sections include strata of upper Campanian and Maastrichtian age (for example, Snipes, 1965; Bramlett and others, 1982). In the northeastern Coastal Plain of South Carolina, the "Middendorf" includes not only the Campanian to Maastrichtian (?) type section but also Turonian (?) to Coniacian beds of weathered Cape Fear Formation (for example, Swift and Heron, 1969; Woolen and Colquhoun, 1977).

A chronostratigraphic comparison of the ages assigned to strata that has been referred to the Middendorf Formation by selected authors is presented in Figure 6; included in this figure is

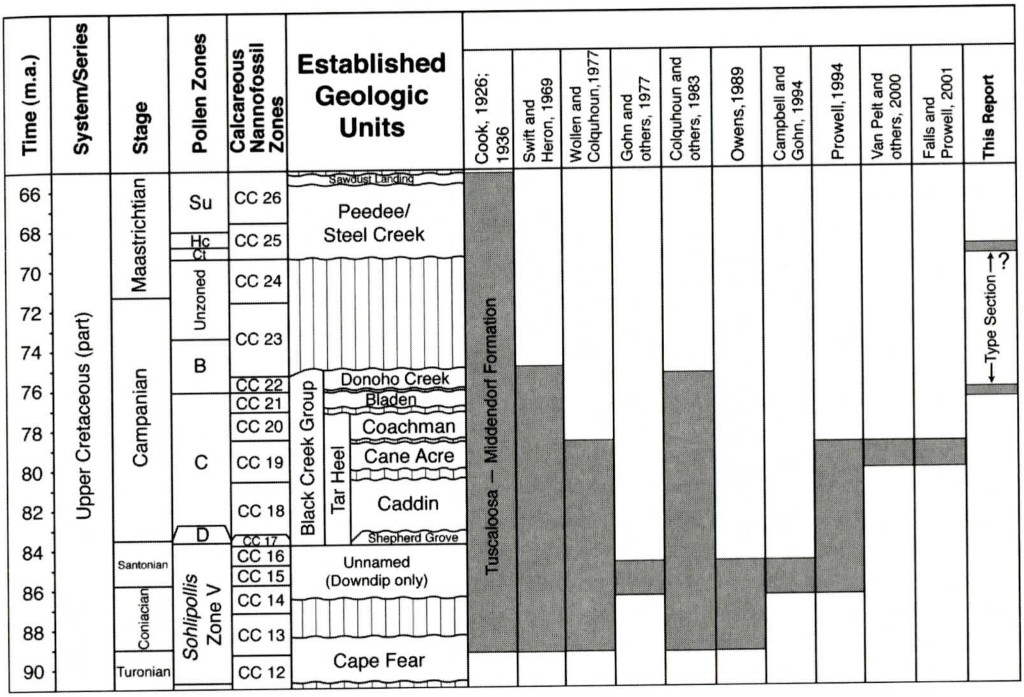

Figure 6. Correlation chart of formal geologic units and strata reported as the Middendorf Formation. (Pollen zones after Christopher and Prowell, in press).

the age of the type locality of the Middendorf Formation as suggested by this study. In addition, the relation of the various "Middendorf" units with unconformity-bounded marine deposits in the outer Coastal Plain is also illustrated in Figure 6. The intention of this figure is to show that: (1) the Middendorf deposits of the Carolinas and eastern Georgia are, in fact, the unconformity-bounded updip equivalents of a number of downdip formations, and (2) most of the strata mapped as Middendorf have little or no correlation with the type section in Chesterfield County, South Carolina.

Sohl and Owens (1991, their figs. 7 and 15) were the first to demonstrate that in the Carolinas, strata of the same depositional unit change from shallow marine to shelfal facies in a generally west to east direction, and this change resulted in assigning different formational names to each facies. For example, clayey shallow marine deposits were called Black Creek Formation and calcareous shelf deposits were called Peedee Formation. Sohl and Owens (1991) also showed that this same scenario was replicated in adjacent unconformity-bounded depositional units. This vertical stacking of similar lithofacies created confusion over the application of the names Black Creek Formation and Peedee Formation for similar facies of different units. Prowell and Christopher (2000a) used palynological correlations and stratigraphic position to add the fluvial components to these units. They extended the work of Sohl and Owens (1991) into western South Carolina and eastern Georgia where the term Middendorf is widely applied to a variety of Upper Cretaceous delta plain deposits. The geologic scenario described above is represented by the line Z–Z' on figure 7, which illustrates the distribution of facies for only one of numerous unconformity-bounded depositional events that occur in the Upper Cretaceous Series of the Coastal Plain. To illustrate the stacked sequence, figure 7 includes a composite of stratigraphic columns showing only the depositional environments; these columns were compiled from core hole and river bluff exposures between eastern Georgia and North Carolina. This figure can be translated into for-

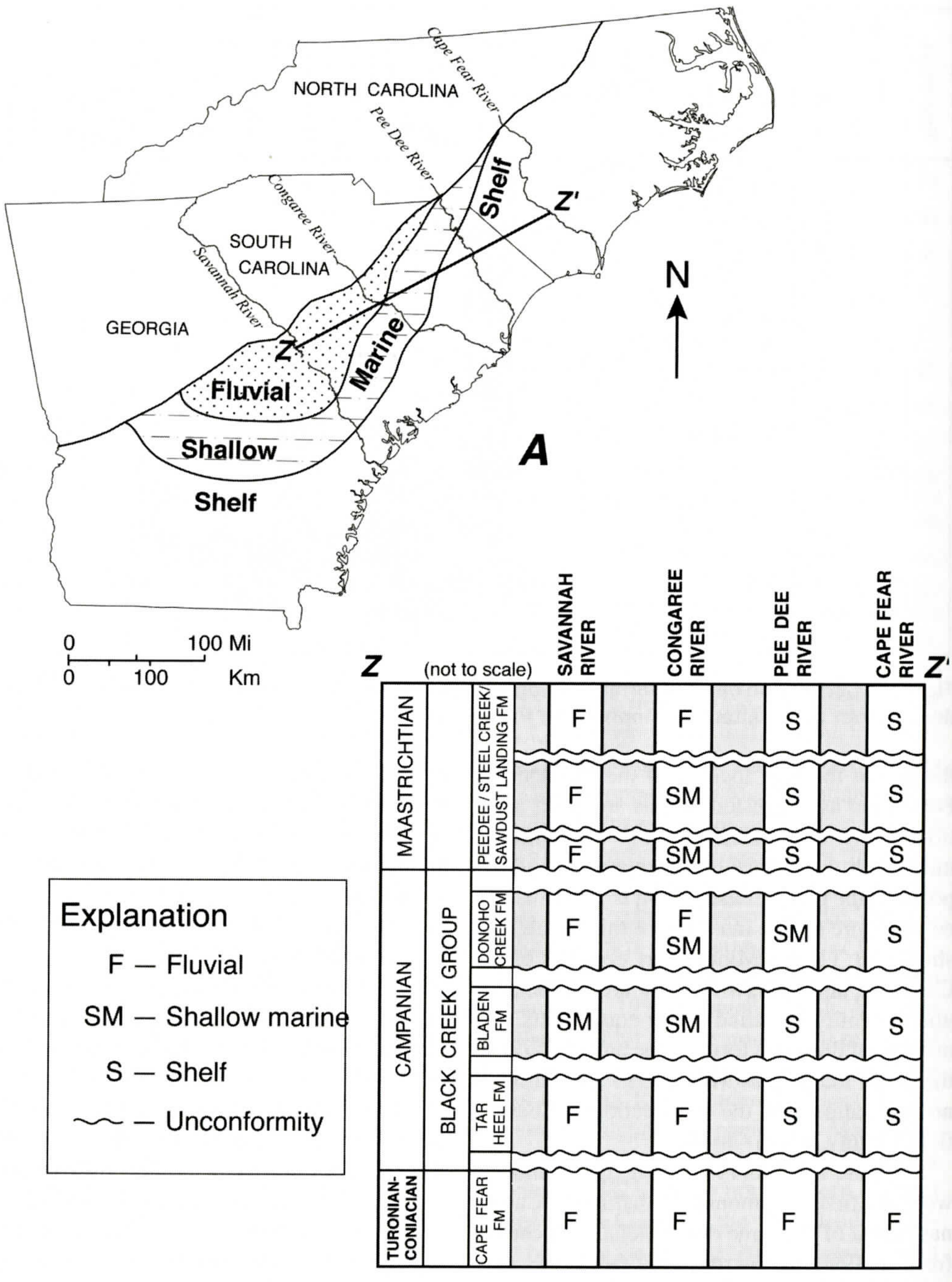

Figure 7. *(A) A c*onceptualization of the general configuration of the ever-changing Late Cretaceous depositional system across Georgia, South Carolina, and North Carolina; *(B)* stratigraphic column illustrating the relation between formations, depositional environments, and regional unconformities at major rivers along section line *Z–Z'*. (modified from Sohl and Owens,1991).

mational nomenclature by assigning the name Middendorf to any fluvial facies aside from the Cape Fear Formation, and the names Black Creek and Peedee to any shallow marine and shelf facies, respectively. Whereas the term Middendorf Formation has primarily a lithologic connotation, most units to which the name has been applied have little mapping or stratigraphic relevance to the type locality of the Middendorf in eastern South Carolina.

The results of this study indicate that a number of units currently assigned to the "Middendorf" need to be reevaluated and (or) renamed. These include, but are not limited to, the Middendorf Formation mapped in western South Carolina by Prowell (1994b), Snipes, (1965) and Bramlett and others, (1982); the UK2 unit of Prowell and others (1985); the Middendorf Formation at Savannah River Site as defined by Fallaw and Price (1995) and Van Pelt and others (2000); the Middendorf Formation in coastal areas of South Carolina as defined by Campbell and Gohn (1994), Gohn (1992), Gohn and others (1977), Hazel and others (1977); and the Middendorf Formation in North Carolina and eastern South Carolina as identified by Cooke (1936), Woollen and Colquhoun (1977), Woollen (1978), Colquhoun and others (1983), and Owens (1989). According to Article 22 of the NASC, a formation may vary in age from one area to another, and for this reason, a liberal definition of the "Middendorf Formation" might allow all of these different kaolinitic sand deposits to bear the same name because lithology and continuity, not age, are the primary factors for defining formations. However, the data show that these deposits do not occupy a unique stratigraphic position, and regional unconformities exist within many of the kaolinitic sand deposits. Downdip, these unconformities separate distinct and well-defined marine units: the Black Creek, Tar Heel, Bladen, Donoho Creek, and Peedee Formations. Combining all of the kaolinitic sands of various ages under one formation name is a method of convenience that has economic significance for exploiting sand, gravel, and clay deposits, but it provides little information regarding the depositional framework of the Coastal Plain. Therefore, it is recommended that the name Middendorf should not be applied to strata that are not directly correlative with the type section in Chesterfield County, S. C. In addition, the various fluvial deposits should be correlated with the appropriate downdip equivalent wherever possible, because the current lithologic formation model is inadequate and misleading with regard to understanding the geologic history of the Coastal Plain.

CONCLUSION

A detailed study of the type section of the Middendorf Formation in Chesterfield County, South Carolina, indicates that the Cretaceous part of the section consists of two depositional units: a fluvial lower unit and a marginal marine upper unit. The stratigraphic and structural position of the type section relative to well-defined formations in surrounding cored holes and outcrops suggests that the two Cretaceous units at the type section are equivalent to either the Bladen Formation, or to parts of both the Bladen and Peedee Formations. If future work can demonstrate that Sloan (1907) or subsequent authors attributed the name Middendorf to either of the two Cretaceous lithofacies present at the Middendorf type section, then the Middendorf should be regarded as a member (facies) of the Bladen Formation of the Black Creek Group or as a member (facies) of the Peedee Formation.

Prowell and Christopher (2000a) and Christopher and others (2000) presented data to show that numerous large delta plains prograded across parts of the Carolinas and eastern Georgia at various times during the Late Cretaceous. These depositional events are bounded by unconformities and most of these events consist of marine and non-marine (deltaic) facies. The fluvial facies of these deltas had many depositional characteristics in common and were readily subject to misidentification, whereas the marine facies were widely recognized as different formations. Regardless of the outcome of the correlation issues associated with the Middendorf type section, neither of the Cretaceous units present at this locality can be correlative, even diachronously, with lithologically similar Coniacian to lower Campanian fluvial strata that are present elsewhere in the study area because they are separated by one or more regional unconformities (Prowell and Christopher, 2000a; Christopher and others, 2000). Therefore, the name Middendorf should not be applied to the older formations previously assigned to the "Middendorf" on the basis of lithologic similarity.

The Middendorf lithology apparently represents the non-marine to restricted marine facies that is stratigraphically equivalent to the majority of the traditional Cretaceous marine formations in the Carolinas and eastern Georgia. In modern sequence models, each of these "Middendorf's" should be described and named relative to it's marine equivalent. The confusion and misunderstanding that surrounds the Middendorf Formation prompts us to recommend restricting the name to strata in the immediate vicinity of the type section. Detailed field mapping will be required to determine if the strata in this area have sufficient lateral extent to maintain the formational status of the unit. And lastly, a sequence stratigraphic model should be superimposed on the traditional lithostratigraphic model currently in use across the Carolina's and Georgia in order to gain a more realistic understanding of the geologic history of the region.

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