NEWLY RECOGNIZED *EN ECHELON* FALL LINES IN THE PIEDMONT AND BLUE RIDGE PROVINCES OF NORTH CAROLINA AND VIRGINIA, WITH A DISCUSSION OF THEIR POSSIBLE AGES AND ORIGINS

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Abstract

Fall zones along streams within the Blue Ridge and Piedmont provinces of North Carolina and Virginia are distributed systematically. Nearly all occur along seven curvilinear trends (fall lines) that parallel the regional tectonic fabric and gravitational gradient of the Appalachian orogen. These seven fall lines are defined and named, and the processes that could have formed them are discussed. The limited available evidence favors a neotectonic origin. The fall lines described here probably formed within the last 2 million years, because late Pliocene fluvial terraces that accumulated along major Piedmont riverways appear to be warped in tandem with adjacent fall zones across at least two of these lines. This indicates that the modern fall lines developed in latest Pliocene or Pleistocene time, after the terrace deposits had accumulated.

Introduction

Although fall zones are an important source of water power in the Piedmont of North Carolina and Virginia, they have been a serious impediment to navigation since the earliest European exploration and settlement. Exploring upstream, colonial era ocean-going ships quickly found their way blocked by major rapids or falls along nearly every major coastal river. These rapids and falls define a prominent linear trace that has been called the "Fall Line" or "Fall Zone" for over a hundred years (for example, Darton, 1894; Clark and others, 1912; Renner, 1927; Dietrich, 1970; Reed, 1981; Hack, 1982; Johnson and others, 1987). This fall line consistently has been located at or near the western edge of the Atlantic Coastal Plain physiographic province (Figure 1, labeled TFL). The origin of "the Fall Line" has been ascribed to tectonic warping (for example, McGee and others, 1891; Hack, 1957; Mixon and Newell, 1977; Reed, 1981), though variation in world eustatic sea level in response to Quaternary glaciation also has played a significant role in shaping its present prominence as a geomorphic feature (Hack, 1957).

The terms "fall line" and "fall zone" have been used more or less interchangeably in the past. Each name has merit for different reasons. Therefore, both names are used here, but in specific and different senses. Along most of their length, the rivers and creeks in North Carolina and Virginia have low and uniform stream gradients. Intermittently, however, streams with low gradients may be interrupted by short stream segments with significantly steeper gradients, usually marked by rapids and/or falls. Because a number of rapids typically succeed each other at close intervals along several miles of each river, "fall zone" is the accurate term to use when referring to one of these regions of steepened gradient along any one river. Whenever a series of fall zones occur in a curvilinear array along adjacent streams and rivers, however, the curvilinear trend defined by these fall zones is best described as a "fall line". Thus, as used here, "fall zones" are short segments of individual stream courses that display abnormally steep gradients, while "fall lines" are groups of "fall zones" that are aligned along curvilinear trends.

Westward of "the Fall Line" at the western edge of the Atlantic Coastal Plain, there has been limited interest in trying to define other fall lines. The only partial exception to this comes indirectly as a corollary to work done on the Blue Ridge escarpment by White (1950), Thornbury (1965, p. 105), and Hack (1982, p. 44, 46). White, in particular, advocated that the abrupt rise along the front edge of the Blue Ridge Mountains in North Carolina and southern Virginia (his "Blue Ridge scarp") was the result of late Cenozoic uplift along a major fracture zone within the western Piedmont (Figure 1, coinciding with feature labeled BRFL south of the number 6A). White noted that several major rivers, including the Green River and the Linville River in North Carolina (Fig. 2, profiles 13 and 14) and the Dan River in Virginia (profile 6B), had gradient profiles that rose sharply across the Blue Ridge Scarp but then flattened out above the scarp. These profiles imply that there is a fall line associated with the Blue Ridge Scarp, even though White never stated this concept explicitly.

Beyond the indisputable observations listed above, White also advocated a model of geomorphic development that included the existence of several peneplanes (surfaces of prolonged erosion and deep soil formation that have become planed and then later uplifted and dissected). In more recent years, the peneplane concept has been discredited in the Appalachian region, especially by Hack (1982) who has strongly argued that the modern topographic relief found west of the Atlantic Coastal Plain represents a geologic terrain largely in dynamic equilibrium between erosion and the hardness of underlying bedrock. Fall lines would not be anticipated within such a dynamically eroding landscape, though sporadically distributed fall zones could occur wherever streams cross from belts of harder rock to belts of softer rock. It is likely that the general acceptance of Hack's model for landscape development has made any search for systematically distributed fall lines seem pointless.

Hack's arguments are sound over broad regions of the Piedmont and Blue Ridge provinces, and he convincingly has shown dynamic equilibrium in many areas of both regions. Yet the detailed analysis presented here of stream gradients across these regions nevertheless indicates the presence of six previously unrecognized fall lines. By definition, these fall lines represent zones where stream profiles are systematically out of equilibrium with their bedrock and thus not in dynamic equilibrium with the rest of the regional landscape.

Delineation of Major Fall Lines in the Piedmont Province

Gradient profiles of major streams crossing the Piedmont and Blue Ridge provinces in North Carolina and Virginia (Figs. 2-7) generally display a stair-stepped pattern (for example, Fig. 3, profile 4 and Fig. 4, profile 6). Most rivers and major creeks flow for long stretches along planar, low-angle gradients without major rapids or riffles. These long regions of quiet flow are separated by much shorter regions with steep, irregular gradients that reflect the presence of numerous riffles, rapids, and even falls. The latter regions of steepened gradient are fall zones, and most of the major rivers display two or more such zones.

Hack (1982) discussed and profiled a number of individual fall zones. Except for "the Fall Line", however, he did not seem to consider the possibility that they might display a systematic distribution across the region. Yet, when the fall zones along individual rivers are plotted in map view (Fig. 8), they clearly align regionally along curvilinear trends that run dominantly northeast-southwest. These trends parallel the structural fabric of the Appalachian Orogen, both as indicated by regional outcrop patterns (Thornbury, 1965) and by a regional deep-rooted gravity gradient east of the Blue Ridge (Bollinger and Wheeler, 1988) (Fig. 8, light-gray area). Seven major linear trends are readily defined by fall zones along rivers and major creeks.

There are only two places where individual fall zones are not associated readily with one of these seven trends: along the Cape Fear River just northeast of Fayetteville, North Carolina and along the Deep River where it crosses the western border of the Sanford basin of Triassic age (Fig. 4, profile 11, designated as **ifz**).

These seven fall line trends, including "the Fall Line" along the eastern edge of the Piedmont, are equally obvious in their geographic and geomorphic expression. Therefore, these seven trends each should be named as distinct geomorphic features. With seven fall lines now recognizable, obviously none can be called **the** Fall Line. For this reason, "the Fall Line" of previous usage in Virginia and northern to central North Carolina is here designated as the **Tidewater Fall Line (TFL)** because along much of its length in Virginia it does represent the head of tide of navigable rivers and because this is the association that has been historically drawn with this particular feature (Dietrich, 1970).

In North Carolina and southernmost Virginia, the fall line that corresponds with the southern part of the "Blue Ridge Scarp" of White (1950) is here termed the **Blue Ridge Fall Line (BRFL)** because it closely matches White's geomorphic boundary in that area. North of the Roanoke River, however, the Blue Ridge Fall Line continues along the front of the Blue Ridge Mountains, while White's postulated northeastward extension of his Blue Ridge scarp trends away to the northeast. The absence of any fall line north of the Roanoke River along the trace of White's Blue Ridge Scarp strongly suggests that the Blue Ridge Scarp does not exist where he hypothesized it in that area. Therefore, the Blue Ridge Scarp either should be restricted to the area south of the Roanoke River as was done by Hack (1982, p. 35), or its trace should be moved westward, north of the Roanoke River, to correspond with the front of the Blue Ridge Mountains as was done by Kesel (1974).

Between the Blue Ridge Fall Line and the Tidewater Fall Line, which bound and define the Piedmont Province on its west and much of its east, are four other fall lines (Fig. 8). The most persistent of these is one that runs from beyond the northern Virginia state line to beyond the southern North Carolina state line. This feature is here termed the **Central Piedmont Fall Line (CPFL)**. Between the Blue Ridge Fall Line and the Central Piedmont Fall Line is a fourth fall line in western North Carolina and southern Virginia that appears to merge, south of

Roanoke, Virginia, with the Blue Ridge Fall Line. This fall line is named the **Western Piedmont Fall Line (WPFL)**. East of the Central Piedmont Fall Line, there are two more fall lines that are here named the **Durham Fall Line (DFL)** and the **Nutbush Fall Line (NFL)**, because of their association respectively with the city of Durham, North Carolina, and the Nutbush Creek Fault Zone in the eastern Piedmont of North Carolina and southeastern Virginia. The relative amplitudes of the fall zones along each one of these fall lines vary widely across the Piedmont and Blue Ridge regions (Figure 9). In general, however, the fall lines attain higher amplitudes southwestward across the region, with the prominent exception being the Tidewater Fall Line, which increases in amplitude toward the north (Reed, 1981).

In addition to these six, east-facing fall lines, there is a seventh but west-facing fall line that can be recognized in southern Virginia and along the North Carolina-Tennessee border. This fall line bounds the southern Blue Ridge and Great Smoky Mountains on their west side and for this reason is here designated as the **Great Smoky Fall Line (GSFL)**. The Great Smoky Fall Line is marked by falls and rapids along the New River and its tributaries and along the eastern tributary streams of the Tennessee River.

Origin of the Fall Lines in the Piedmont and Blue Ridge regions

The linear alignment of fall zones along seven major regional fall line trends indicates that some factor of regional importance is controlling their distribution. Three possible hypotheses can be put forth to explain the origin of these fall lines: (1) the fall lines reflect unequal rates of erosion of linear belts of rock that have different hardnesses within the Piedmont and Blue Ridge provinces; (2) the fall lines reflect climatically driven changes in the hydraulic gradient and flow volume of major streams, which in turn have systematically and cyclicly altered the profiles of the various rivers across the region; or (3) the fall lines reflect late Cenozoic neotectonic uplift within the Piedmont and Blue Ridge provinces. Any of these hypotheses, or a combination of them, could account for the development of seven discrete fall lines across the Piedmont and Blue Ridge regions.

Hypothesis 1: Differential rock hardness. An adjustment of river gradients to rock hardness can be demonstrated locally in numerous areas of the Piedmont and Blue Ridge (Hack, 1982). Similarly, differential rock hardness usually determines which areas are rapids and which areas are slack water regions within individual fall zones. Yet, despite this frequent correlation, there also are many areas where the correlation between rock hardness and river gradients is poor or nonexistent. Thus hypothesis 1, in and of itself, cannot account for all of the observed river gradient patterns.

The frequent poor correlation between rock hardness and stream gradients is best illustrated by the variable response of river gradients to rock hardnesses in and around Triassic-Jurassic Newark Supergroup basins within the Piedmont (Figure 8, dark-gray areas). Generally speaking, the Triassic and Jurassic sedimentary rocks of the Newark Supergroup basins are much softer than the crystalline Piedmont rocks that surround them. This is implicit in the term "Triassic lowlands" (for example, Roberts, 1928), which has been used to convey the fact that rocks within Triassic-Jurassic basins generally are more deeply eroded and lie topographically at lower elevations than surrounding Piedmont crystalline rocks. The one exception to this pattern are Jurassic diabase rocks, which can be very resistant to erosion where they are not pervasively fractured.

Contrary to what would be expected, if bedrock hardness were the sole determinant of stream gradients, river profiles across the Triassic-Jurassic basins in Virginia (Figs. 3 and 4) display striking variability in the relationship between river gradients and the bedrock lithologies of these basins. Along the Potomac River (Fig. 3, profile 1), the western edge of the Culpeper basin has no discernable signature on the river profile, despite the fact that the Potomac flows across erosionally resistant, mountain-forming quartzites and greenstones immediately before it crosses the much softer Culpeper basin rocks. Only much farther west, at the foot of the Blue Ridge, is there a gradient anomaly and rapids. Uniform gradients also occur where the James and Appomattox rivers cross the Richmond, Scottsville, and Farmville basins (profiles 4 and 5), even though there is a strong contrast in rock hardness between the basin sediments and their surrounding metamorphic and igneous rocks. Along the South Anna River (profile 3), a gradient anomaly occurs across the Taylorsville basin, marking the position of the Tidewater Fall Line

(TFL). Yet this gradient is subdued when compared to TFL river gradients to the north (profile 2) and south (profile 4). West of the Taylorsville basin, however, the river gradient steepens abruptly and becomes very similar to the TFL gradient along rivers to the north and south. This pattern, unlike the ones previously cited, strongly suggests that softer sedimentary rocks in the Taylorsville basin have eroded much more rapidly than the gneisses immediately west of the basin, so that the steepest gradient of the TFL has migrated upstream (westward) through river bed erosion to a position that presently is controlled by differential rock hardness. Even so, despite the fact that the profile of the TFL along the South Anna is now subdued in its eastern reaches because of differential erosion controlled by varying rock hardness, the toe of this profile has not migrated upstream and remains recognizably anchored at the western edge of the Coastal Plain as it is elsewhere along the Tidewater Fall Line.

Totally anomalous gradient-to-bedrock-hardness relationships are found in the Culpeper basin along the Rappahannock and Rapidan Rivers (Figure 3, profile 2). Along these rivers, the toe of the Central Piedmont Fall Line (CPFL) is anchored along the eastern edge of the Culpeper basin, so that the basin rocks support the steepened gradient. The CPFL is relatively higher along the Rappahannock River, which can be attributed to the presence in that area of a body of diabase in the eastern part of the basin that is resistant to erosion. But even along the Rapidan, which flows through the Culpeper basin over siltstones and sandstones, the anomaly clearly is present, even though the rocks at and upstream of the anomaly are softer than the rocks below the anomaly. This pattern cannot be explained by relative rock hardnesses.

Similarly, the Rappahannock, like the Potomac, crosses from the western Piedmont into the Culpeper basin with no discernable gradient anomaly, even though the river flows from relatively hard rocks onto relatively soft rocks. In contrast, the Rapidan River displays a mild gradient anomaly across this same structural boundary. It seems significant that this anomaly on the Rapidan is roughly equivalent in height to the "missing" height of the Rapidan River anomaly where it crosses the eastern edge of the Culpeper basin (in comparison to the nearby profile of the Rappahannock River). Therefore it seems likely, as in the case of the TFL across the Taylorsville basin along the South Anna River, that the Rapidan has eroded rapidly into the soft rocks of the Culpeper basin west of the CPFL, thereby producing an exceptionally wide fall zone which has spread far upstream to produce a concave-up profile.

This contrast in the profiles of the Rappahannock and the Rapidan rivers across the CPFL is striking. Where they cross the Culpeper basin, both rivers are comparable in water volume and geographically (and hence climatically) very close, yet they display very different stream profile patterns relative to their bedrock floors. This contrast can be explained readily by geologically recent uplift on the east side of the Culpeper basin in this area, but it cannot be explained adequately by a process of dynamic equilibrium that is controlled simply by differences in bedrock hardness across this region.

Similarly diverse relationships between stream gradient and bedrock hardness occur elsewhere where rivers cross Newark Supergroup basins. For example, along the Staunton River (Fig. 4, profile 6), the Central Piedmont Fall Line includes the Triassic rocks of the Danville basin within its steepened profile, and it is not at all obvious from the river gradient profile that the Triassic rocks are softer than the rocks to their east and west. However, despite the absence along the river profile of any contrast between the sedimentary Triassic rocks in the Danville basin and the metamorphic rocks immediately to their east and west, the lowland topography within the Danville basin north and south of the area where the Staunton River crosses it readily attests to the generally softer and more easily eroded character of the Triassic rocks relative to the surrounding metamorphic rocks.

The profile of the Tar River across the Nutbush Fall Line (profile 9) is separable into two quite discrete zones of steepened gradient across metamorphic rocks separated by a region of low gradient across softer rocks of the Durham basin. In this case the Tar River, unlike the Staunton River, appears to have responded strongly to the contrast in rock hardness between the Durham basin and the surrounding metamorphic rocks. A somewhat similar pattern possibly is displayed along the Deep River west of the Sanford basin (profile 11), where a seemingly isolated fall zone (labeled "ifz") may represent a similar but much longer upstream migration of the head of the Durham Fall Line (DFL) across the soft Triassic rocks of the Sanford basin. Such an hypothesis is supported by the fact that the gradient profile along the Deep River across the DFL is anomalously low when compared to the gradient profile along the nearby Neuse, Haw, and Rocky rivers where they cross the DFL (profiles 10 and 11). Thus, as along the South Anna and the

Rapidan, there probably has been a strong local response to bedrock hardness where the toe of a fall zone lies near or at the eastern edge of a Newark Supergroup basin. In this case, however, the amount of upstream migration of the fall zone is considerably greater than that observed elsewhere.

Another remarkable profile of a different type also occurs along the Neuse River (Figure 4, profile 10). The Neuse flows out of the Piedmont into the Atlantic Coastal Plain without any discernable gradient anomaly whatsoever and continues eastward for about thirty miles without significant gradient change. At that point, however, the river has cut deeply enough through the Coastal Plain sedimentary cover to expose an isolated belt of metamorphic rocks that lies along the trend of the Tidewater Fall Line (Fig. 8). Here, the river falls slightly but perceptibly over a series of rapids on the metamorphic rocks and then continues eastward along a very low gradient. This river demonstrates that, even though a fall zone is the normal boundary between the Atlantic Coastal Plain and the Piedmont, it is by no means an obligatory boundary. The reason for this exception seems to be closely related to the fact that the Neuse River crosses the Tidewater Fall Line (TFL) within the Coastal Plain. Along this river, where the Atlantic Coastal Plain boundary turns abruptly westward in North Carolina but the Tidewater Fall Line continues southward (Fig. 8), correlation disappears between rock hardnesses and river gradients.

Hypothesis 2: Climatically Driven Cycles. The second hypothesis, that systematic cyclic climate changes have produced the observed fall lines, readily would explain the *en echelon* arrangement of these features. As water volume and bed load changed systematically through time, the various rivers in turn would cyclicly lower their streambeds more rapidly and then less rapidly, sending a series of steepened gradient waves working their way up the stream profiles. Such a pattern also would be consistent with the glacial-interglacial cycles that have changed sea level and dominated the Earth's climate over the past several million years.

Yet any such pattern also should have produced several effects that are not observed. Each wave of upstream erosion should carry through the entire region, which it demonstrably does not in the case of the Durham Fall Line and the Nutbush Fall Line. Successive waves of gradient anomalies should be recognizable symmetrically up the course of streams flowing both east and west from the Appalachians, but no pattern can be found in the New and Tennessee River valleys comparable to the complex pattern seen among the eastward-flowing streams. The Great Smoky Fall Line is the only major gradient anomaly within the Blue Ridge or Valley and Ridge region in the Kanawha and Tennessee drainage basis, and each of those river systems have only one other gradient anomaly where they cross the Appalachian Plateau region (Figures 5 and 6). Additionally, a few large rivers such as the Shenandoah (Figure 7), show no development of gradient anomalies along nearly their entire length.

A final problem with a climatic origin for the fall lines is that successive waves of gradient anomalies should migrate upstream at a rate roughly in proportion to the volume of water that each stream carries. This is demonstrably not the case for large rivers show no systematic tendency for their fall zones to lie at a more westerly location than the correlative fall zones of adjacent much smaller rivers. Thus, a climatically controlled, water volume/bedload model fails to explain many of the most salient features of the fall lines that are recognized here.

Hypothesis 3: Neotectonics. The preceding observations concerning river profiles in North Carolina and Virginia demonstrate that climatic fluctuations cannot fully explain the distribution of the observed fall zones. Similarly, rock hardness and geomorphic expression, although sometimes correlated, are by no means always correlated and may even be inversely correlated. Significantly, the best correlations between rock hardness and geomorphic expression occur only in areas immediately adjacent to the upstream side of the seven fall lines defined here. This can be most simply explained as a result of tectonic uplift along the downstream edge of these fall zones, which has caused stream rejuvenation on the upthrown side that locally highlights contrasts in rock hardness. Away from these neotectonic fronts, where streams have not been rejuvenated, streams flow along equilibrated gradients that have been established so long that they no longer respond to the hardness and fabric of the underlying bedrock. Thus, a regional survey of river profiles strongly suggests that hypothesis 3 (tectonic control) is the dominant cause of the existing Piedmont fall lines, that hypothesis 1 (rock-hardness control) is true only locally and occurs directly as a consequence of hypothesis 3, and that hypothesis 2 (climatic control) does not adequately explain the observed patterns.

Two other lines of independent and equally compelling evidence also indicate localized tectonic motion along certain of these fall lines. One line of evidence for tectonic motion along two of the fall lines can be seen along the Roanoke River and its Staunton River tributary. Along these rivers, three levels of terrace gravel have been traced by the author from the Atlantic Coastal Plain upstream to the community of Altavista, Virginia (Fig. 10). Across the Nutbush Fall Line (NFL) and the Central Piedmont Fall Line (CPFL), each terrace has been warped upward nearly in tandem with the profile of the existing fall zones. These warped terraces strongly indicate that the fall zones resulted from tectonics, with most or all of the warping taking place since the terraces formed. The other line of evidence lies in the strong correlation along most of their length between the location of the Nutbush Fall Line and the mapped position of the Nutbush Creek Fault Zone (Stoddard and others, 1991). This association is so intimate that it would appear to be causal rather than coincidental. Here, better than anywhere else, a consistent geographic correlation between a fall line and a known major tectonic structure can be demonstrated.

Age of Fall Lines in the Piedmont

If the seven fall lines here defined were formed by tectonic processes, this strongly implies that there has been geologically recent movement along their trends. If these fall lines had a geologically ancient origin, then by now they would have eroded away and the rivers flowing across them would have re-equilibrated their profiles along their lengths. Based on the relatively youthful geomorphic characteristics of the modern Appalachian Mountains, Hack (1982) has argued that the existing Appalachians represent a much more recent and basically different mountain chain than the classic Appalachians of the Paleozoic or the block-faulted ranges of the early Mesozoic Newark rift system. Unfortunately, direct stratigraphic evidence for the origin of the modern Appalachians has been largely stripped away by the processes that formed them during the late Cenozoic. Even so, evidence from the depositional history recorded within the Atlantic Coastal Plain immediately to the east (Fig. 1), where much of the sediment stripped from the Appalachians and Piedmont has been deposited, provides some constraint on the timing and sequence of events that have occurred (Poag and Sevon, 1989).

Although a major prolonged episode of rapid deposition within the Atlantic Coastal Plain occurred from the time of initial Atlantic basin rifting up through the mid-Cretaceous, Gibson (1970) has documented that deposition in the Atlantic Coastal Plain slowed dramatically throughout Late Cretaceous and Early Tertiary time. This major decline in deposition rate was accompanied by an early Paleocene high sea-level stand that near Washington, D.C., was at least 400 feet higher than sea-level today (Gibson and others, 1991). While the relative contributions of tectonics and global sea-level change to this inundation have not been worked out, both the dramatic decline in sediment influx into the Atlantic Coastal Plain and the occurrence of a major marine incursion indicate that by Early Tertiary time the ancient Appalachians were no longer shedding massive volumes of sediment toward the Atlantic Coastal Plain. This suggests that the Appalachian region had been reduced by that time to an area of low relief that could not be characterized as a mountainous belt. Although McCartan (1989) documented a minor influx of labile heavy minerals into the Coastal Plain in early Eocene time, which suggests modest early Eocene Piedmont erosion down to bedrock, the lack of rapid sedimentation in the Coastal Plain indicates that the Piedmont and Appalachian regions probably were deeply weathered and had low relief throughout most of Late Cretaceous and Early Tertiary time.

The best estimator for the time of formation of the modern Appalachians is the significant influx of labile heavy minerals (McCartan, 1989) that occurs in the late Miocene Windmill Point Member of the St. Marys Formation in Virginia (Mixon and others, 1989). The Windmill Point Member of the St. Marys Formation was deposited during Foraminiferal Zone N16 (Mixon and others, 1989), which indicates that somewhere between 10 and 7 million years ago (Berggren and others, 1985) the modern Appalachians began to rise and shed large volumes of fresh mineral grains and rock fragments into the Coastal Plain. This age bracket corresponds well with Hack's (1982, p. 44) independently derived estimate that it probably has taken between 7.5 and 15 million years for the Linville River to lower its upper valley a vertical distance of 500-1000 meters through the Grandfather Mountain window. Although Hack argued cogently that the changes in the incisement of the Linville River were not accompanied by any large shift in the position of the eastern continental divide in that area, this episode of uplift apparently did expand the drainage basins of at least some rivers in Virginia westward, for about this time the first identifiable clasts of rocks from beyond the Blue Ridge appear in the western Coastal Plain along the James River (Weems, 1990). Labile heavy minerals continued to flood into the Coastal Plain in latest late Miocene time (N17 or 7 to 5 million years ago) during deposition of the Eastover Formation (McCartan, 1989).

The highest (and oldest) terrace deposits preserved in the western Coastal Plain are correlative with either the St. Marys or Eastover Formations (Weems, 1986; Fleming and others, 1994). These deposits contain numerous clasts of saprolitized metamorphic and igneous rocks. Such clasts could not have been transported in their present degraded state, so they must have been introduced as fresh fragments of Piedmont bedrock and then later been saprolitized after deposition. The rate at which saprolite forms in the Piedmont (about 1 m/ 500,000 years as estimated by Pavich and Obermeier, 1985) easily is rapid enough to have allowed *in situ* saprolitization of these clasts in the 5 million years since Miocene time. While less precisely dated than the sediments studied by McCartan (1989), these high-level Miocene gravel deposits provide independent corroborating evidence of erosion and transport of large volumes of fresh Piedmont bedrock into the western Atlantic Coastal Plain in late Miocene time.

By the early Pliocene, this first major pulse of Late Tertiary uplift appears to have waned. Deposits along the inner edge of the Coastal Plain in central and southern Virginia, correlative with the Yorktown Formation, include gravels that are dominated overwhelmingly by quartz and a near absence of saprolitized igneous or metamorphic clasts (Weems, 1986). This suggests that in early Pliocene time the dominant source of sediment for the western Coastal Plain either was from the reworking of late Miocene sedimentary deposits (now stripped from the Piedmont and beyond), from erosion of saprolites that had begun to form and blanket the Pliocene Piedmont landscape, or a combination of both sources. By the latest Pliocene, however, a renewed influx of metamorphic and igneous clasts into the Bacons Castle Formation (Weems and others, 1996), now mostly saprolitized, indicates that uplift had resumed. Unsaprolitized metamorphic and igneous clasts also constitute a significant fraction of rock fragments found in Quaternary and recent terrace deposits in the western Coastal Plain Province of Virginia (Weems, 1986). Thus, erosional and depositional patterns in the Atlantic Coastal Plain indicate that the modern Appalachians underwent two major pulses of uplift, one during the late Miocene (between 10 and

5 million years ago) and one in late Pliocene and Quaternary time (between 2 million years ago and the present).

The highest and oldest late Miocene gravels of the western Coastal Plain underlie a terrace surface that has been warped extensively since it formed. As a result, correlative gravels now underlie a strongly distorted terrace surface that has elevations between 415 and 520 feet in and near Washington, D.C. (Fleming and others, 1994; Drake and Froelich, 1997), elevations of 300 to 400 feet near Richmond, Virginia (Johnson and others, 1987), elevations of 320 (Winker and Howard, 1977) to 540 feet (personal observation) in South Carolina, and elevations of only 100 to 200 feet in Georgia (Winker and Howard, 1977). Faulting within deposits of this terrace appears to be more pervasive than in younger terraces (Prowell, 1983; Johnson and others, 1987; also Wayne L. Newell has unpublished photographs of high angle reverse faults cutting deposits of this terrace at Tyson's Corner, Fairfax County, Virginia). In contrast, Pliocene and younger terraces scarcely have been warped along the Tidewater Fall Line (Mixon, 1978), even though some small faults with a few feet of displacement have been documented in beds of Yorktown (Duplin Member) age (Johnson and others, 1987). The inland edge of the terrace that caps the Yorktown Formation lies at an elevation of about 265 feet in northern Virginia (Mixon, 1978), at about 275 feet at the Virginia-North Carolina line (personal observation), and at about 270 feet in central South Carolina (Colquhoun, 1965). Thus, at least in the western Coastal Plain, available evidence suggests that late Miocene tectonic warping was much more extensive and more pervasive than tectonic warping in late Pliocene and Quaternary time.

Because of extensive erosion during the prolonged time since the Miocene uplift, much of the volume of Piedmont and Appalachian rocks uplifted during the late Miocene tectonic event probably has been weathered and eroded away, as evidenced by the strongly inverted topography associated with the highest level of late Miocene gravels along the Tidewater Fall Line (for example, Goodwin, 1980; Johnson and others, 1987; Drake and Froelich, 1997). The extensive erosion has removed most obvious evidence for this event, and all that appears to be left from this tectonic event in the Piedmont are monadnocks or inselbergs (Figure 11) (Kesel, 1974), as well as the remnant high areas cited by White (1950) west of the Blue Ridge Scarp in western North Carolina.

It is probably significant, however, that all but two of the several hundred inselbergs documented in the Piedmont occur west of the Central Piedmont Fall Line in Virginia and west of the Durham Fall Line in North Carolina (Fig. 11). This suggests that both of those fall lines mark zones of late Miocene tectonic activity because they seem to bound the eastern margin of the uplifted areas that were eroded to produce the inselbergs. Additionally, at least one area in northern Virginia not associated with any existing fall line has been associated with tectonic vertical displacements of this general age (Weems, 1993; marked by dotted line on Figure 8 and here designated as the Stevensburg scarp). Because available evidence indicates that most tectonic warping and faulting along the Tidewater Fall Line occurred prior to mid-Pliocene time (Mixon and Newell, 1977; Mixon, 1978), the bulk of tectonic activity in that area also occurred before the mid-Pliocene. No evidence can be brought to bear concerning whether or not the initial Miocene episode of uplift affected the trend of the Nutbush Fall Line, the Western Piedmont Fall Line, the Blue Ridge Fall Line, or the Great Smoky Fall Line.

In the early and mid Pliocene, the Piedmont and Blue Ridge were extensively eroded, ultimately producing the "Asheville Peneplain" of White (1950), the western Piedmont plateau, and the Chesterfield terrain of Johnson and others (1987). Although some earlier workers characterized this erosional surface as a peneplane, it seems unlikely that erosion proceeded long enough to produce a truly peneplaned land surface. Even so, extensive saprolites developed across the landscape, indicating a prolonged interval of time during which erosion failed to keep pace with weathering. During this same time interval, river gradients across the Piedmont decreased enough to permit the develop of three extensive terrace-gravel deposits at successively lower levels along larger rivers such as the Potomac, the Rappahannock, the James, and the Roanoke. These terrace deposits have been traced by the author down the Rapidan, Rappahannock, Staunton, and Roanoke rivers into the Atlantic Coastal Plain (Fig. 10).

The upper surfaces of these terraces can be correlated respectively with the upper surfaces of the Duplin, Chowan River, and Bacons Castle Coastal Plain terrace units (Fig. 10). This correlation indicates that the highest well-developed terrace along the Piedmont rivers formed during the same high sea-level stand that deposited the Duplin member of the Yorktown Formation in mid-Pliocene time around 2.8 million years ago (Hazel, 1983; Barrett and others, 1992). The top of this river terrace deposit enters the Coastal Plain at the same elevation as the toe of the Thornburg Scarp (Mixon, 1978). The middle terrace unit traces into an unnamed terrace unit that probably correlates with the late Pliocene Chowan River Formation, deposited about 2.5 million years ago (Hazel, 1983), which is the only stratigraphic unit documented between the Duplin and Bacons Castle terraces. This unnamed terrace unit tops at about 240 feet elevation and is bounded updip by the Chippenham scarp (Johnson and others, 1987). The third and lowest Piedmont terrace can be traced into the Bacons Castle Formation, which has not been dated directly but can be inferred to be about 2.0 million years old by its position above the Chowan River Formation and its position beneath the early Pleistocene Windsor Formation (Johnson and others, 1987). The upper surface of the Bacons Castle tops at about 175 feet elevation at the base of the Broad Rock scarp (Johnson and others, 1987).

These upland Piedmont terraces probably formed, at least in part, due to exceptionally high mid to late Pliocene sea levels that were caused by an extensive Pliocene melt-down of the Antarctic ice sheet (Barrett and others, 1992). Once the Antarctic ice sheet had largely reformed, toward the end of the Pliocene, sea levels no longer rose high enough to affect river gradients across the Piedmont region west of the Tidewater Fall Line. Therefore, Pleistocene Coastal Plain terrace surfaces, correlated westward by the author along the Roanoke and Rappahannock rivers, do not rise westward in elevation high enough to crest above the Tidewater Fall Line.

After the episode of Pliocene erosion, partial planation, and terrace formation, the Pliocene terrace deposits along the Roanoke and Staunton rivers were warped as a group across the Central Piedmont Fall Line and the Nutbush Fall Line (Fig.10). This indicates that warping must have occurred after the deposition of the late Pliocene Bacons Castle formation, or within the last 2 million years. This same episode of uplift probably also caused the regional Pliocene erosional surface on the Piedmont to be broken into three presently discernable topographic segments, which can be recognized in the landscape today (Figure 12). To adduce further evidence, the degree of terrace warping is comparable to the existing gradient anomalies along the Roanoke and Staunton rivers (Fig. 10), which thereby indicates that the existing gradient anomalies across the central Piedmont Fall Line on the Staunton River and across the Nutbush Fall Line along the Roanoke River are products entirely of the second (late Pliocene-Quaternary) episode of tectonic uplift.

There appears to be a subtle regional topographic break between the uplands of the western Piedmont plateau and the uplands of the Chesterfield terrain, which shows up in a topographic profile across southern Virginia (Figure 12). This break occurs at the position of the Central Piedmont Fall Line and thus probably formed concurrently in latest Pliocene and/or Quaternary time. Because the saprolite profiles on the western Piedmont plateau and the Chesterfield terrain are quite similar in thickness and development (personal observation), despite the fact that the western Piedmont soils today are in a region of higher relief than the Chesterfield terrain soils, the origins of these thick saprolites may be in the Pliocene weathering episode between the two major episodes of tectonic uplift. This conclusion is in accord with the estimated rates of saprolite formation in the Piedmont presented by Pavich and others (1989, p. 49) and their conclusion that the present saprolite profiles probably do not result from the existence of a peneplane across the Piedmont that formed prior to the Pliocene.

Recent tectonic activity in central Virginia (Taber, 1913; Hopper and Bollinger, 1971, 1972), as well as the sharply convex upward profile of the James River across the Central Piedmont Fall Line near Scottsville (Fig. 3, profile 4), suggests that significant late Quaternary fault movement has occurred along that part of the Central Piedmont Fall Line. This indication of recent tectonism along the CPFL in the James River valley is similar to the pattern found along the CPFL in the Staunton River valley (profile 6). Yet these similar patterns contrast with the seemingly minor recent movement along the CPFL in the intervening Appomattox River valley (profile 5). (Interestingly, earlier strong uplift along the CPFL in the late Miocene probably caused the Appomattox to be decapitated, with its headwaters becoming deflected northeastward toward the James -- compare the geometry of drainage basins 4 and 5 in Fig. 1.) Similarly, the profile of the James River across the Blue Ridge Fall Line (Fig. 4, profile 4A) appears rather subdued when compared with the significant topographic disparity between the Blue Ridge and the Piedmont monadnocks east of it (Figure 12). This suggests that movement there has not occurred nearly as recently as it has farther southwest in North Carolina where the Blue Ridge scarp (and modern seismicity associated with it) suggests extensive Quaternary movement along this sector of the BRFL (White, 1950). Thus, within the latest Pliocene-Quaternary episode of tectonic activity along the various fall lines, it seems likely that movement along individual faults within each fall zone has been temporally intermittent and geographically sporadic.

Evidence for late Cenozoic faulting in the Piedmont Province

Despite the abundant circumstantial evidence presented here for neotectonic activity in the Piedmont and Blue Ridge, relatively few recent faults have been identified from those areas (Fig. 8). Prowell (1983) summarized the older literature in this regard, and only two more faults have been documented since then (Pavlides and others, 1983; Johnson and others, 1987). There are two major impediments to recognizing recent fault movement in the Piedmont, however. One is the relatively sparse detailed geologic coverage of this area, and the other is the scarcity of late Cenozoic sediments over most of this region. Many mapped faults might have been active in the late Cenozoic, yet failed to leave any obvious record of their movement.

There is a cluster of faults in the vicinity of Raleigh, North Carolina, that do not show any clear correlation with the fall line trends defined here, though they do co-occur with the isolated fall zone along the Cape Fear River northeast of Smithfield, North Carolina. These small surface faults have been used as evidence for a large NNE-trending fault-zone beneath the Coastal Plain by Markewich (1985) and Marple (1994). Other faults, however, generally do correlate with the fall lines mapped here. Therefore, available evidence is suggestive, though not yet conclusive, that late Cenozoic movement along older fault zones may be associated with the seven geomorphic fall line trends that here are documented in the Piedmont of North Carolina and Virginia. Conversely, the equilibrated stream profiles between fall zones, except along the Cape Fear River northeast of Fayetteville, North Carolina (Fig. 3, profile 11), suggest that neotectonic faulting probably will not be found in any abundance within the intervening blocks that are overlain by consistently low-gradient streams.

The dominant sense of motion along faults producing fall zones within the Piedmont must be up on the west side where stream incisement has occurred, but whether this motion is due to normal or reverse faulting, and with or without a strike-slip component of motion, remains undemonstrated along these zones. Prowell (1983) documented a number of local neotectonic fault orientations and motions in the eastern United States, but he concluded that the dominant orientation throughout the eastern United States appears to be northeast-trending high-angle reverse with a minor strike-slip component and a steep dip to the southeast (Prowell, 1988). This pattern might be anticipated along the Piedmont fall lines.

The existence of a significant gravity gradient across the western Piedmont region (Fig. 8, light-gray area), as documented by Bollinger and Wheeler (1988), provides a driving force for regional linear fault-belts across the Piedmont in response to tectonism. This gravity gradient marks a boundary zone where a lighter and thicker portion of the Earth's crust west of the anomaly is juxtaposed against a thinner and denser portion of the crust that lies east of the anomaly. Two adjacent blocks of crust, with different thicknesses and densities, probably will respond differently to a change in the local tectonic environment. For example, if erosion reduced the Appalachian-Piedmont landscape to a nearly featureless plane, the inherent differences in the crustal thickness east and west of the Blue Ridge would cause unequal isostatic rebound across this area proportional to the difference in crustal thickness and/or density. Areas of thicker and lighter crust west of the Blue Ridge would rebound more strongly than areas of thinner and denser crust east of the Blue Ridge, and this would produce stress along the boundary between these two dissimilar blocks of the Earth's crust. Faulting then would be the simplest mechanism for dissipating the resultant stress in the crystalline crust, especially in this area where the crust is already pervasively fractured by relict northeast-trending faults of Paleozoic and Mesozoic age.

Summary

Gradient profiles of major rivers and creeks crossing the Piedmont and Blue Ridge provinces of North Carolina and Virginia demonstrate the presence of numerous fall zones along these streams. When plotted geographically, nearly all of these fall zones occur along seven discrete linear trends within the Piedmont and Blue Ridge Provinces. These trends from west to east are here named the Great Smoky Fall Line (GSFL), the Blue Ridge Fall Line (BRFL), the Western Piedmont Fall Line (WPFL), the Central Piedmont Fall Line (CPFL), the Durham Fall Line (DFL), the Nutbush Fall Line (NFL), and the Tidewater Fall Line (TFL).

Comparison of river profiles with underlying bedrock characteristics indicates that stream gradient anomalies in the Piedmont and Blue Ridge Provinces do not correlate consistently with underlying rock hardness or type. Instead, the fall lines seem to reflect neotectonic uplift along seven major fracture trends within the Piedmont and Blue Ridge provinces, one of which corresponds along much of its length with the Nutbush Creek Fault Zone. Immediately upstream of these fall lines on the margin of upthrown blocks, rivers either are adjusted to the hardness of underlying bedrock or occasionally are adjusted inversely to bedrock hardness. Away from the fall lines, relative bedrock hardnesses do not appear to influence river gradients.

The Atlantic Coastal Plain province east of the Piedmont has served as a sediment sink for much of the sediment shed from the Piedmont Province in late Mesozoic and Cenozoic time. Analysis of these Piedmont-derived sediments suggests that the modern Appalachians have formed only within the last ten million years. Two major episodes of uplift can be documented, the first between 10 and 5 million years ago (late Miocene) and the second between 2 million years ago and the present (latest Pliocene and Quaternary). The earlier episode of uplift involved movement along at least the Tidewater Fall Line, the Central Piedmont Fall Line, and the Durham Fall Line. Additionally, upland geomorphology indicates that there was late Cenozoic displacement along a fracture zone in northern Virginia along the western margin of the northern Culpeper basin and across the basin in the vicinity of Stevensburg. Because this offset is not associated with any existing fall line, it probably occurred prior to the latest Pliocene-Pleistocene uplift that formed the existing fall lines. No evidence is available to indicate whether or not there was any uplift along the Great Smoky Fall Line, the Blue Ridge Fall Line, or the Western Piedmont Fall Line at that time. In contrast, geomorphic offsets along the Nutbush Fall Line are no greater than the height of the existing Nutbush Fall Line, and Pliocene river terraces are warped to a degree closely matching the height of the existing fall line. Together, these observations suggest that the Nutbush Fall Line did not exist prior to the late Pliocene.

The second episode of uplift involved at least six of the seven fall lines. The Tidewater Fall Line may simply represent geologically recent exhumation of a late Miocene scarp by downward erosion through a Coastal Plain cover that buried this feature shortly after it formed. So far, there is little to no indication of any vertical offset of Pliocene terraces across this feature, which would be expected if there had been significant latest Pliocene or Pleistocene vertical movement along this trend. Along the other six fall lines, however, there is considerable evidence for latest Pliocene and/or Pleistocene vertical movements. Significant differences in the height of fall zones along successive rivers, where each crosses a particular fall line, strongly suggests that uplift along the length of each fall line has been sporadic, with movement occurring for a while in one area and then shifting to another area (Fig. 9). Small earthquakes in and near Scottsville, Virginia, along the Central Piedmont Fall Line, as well as in western North Carolina and South Carolina near the Blue Ridge Fall Line, indicate that the second episode of tectonic uplift has not yet run its course.

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FIGURES

1. Map showing location of the river systems profiled in the following three figures. TFL = Tidewater Fall Line, BRFL = Blue Ridge Fall Line. Gray tone covers the Atlantic Coastal Plain. Most numbers lie immediately above the river system to which they refer, except for 4A and 6A, which lie beneath them and 15 and 16 which lie to the left of them. Numbers are correlated to profiles in the following six figures.

2. River gradient profiles for Piedmont rivers that originate west of or on the Blue Ridge Fall Line. BRFL = Blue Ridge Fall Line, WPFL = Western Piedmont Fall Line. River locations are shown in Figure 1. Triangular wedges along profiles represent dams and lakes. Profiles were compiled from U.S. Geological Survey 7.5-minute topographic maps (scale 1:24,000). Vertical scale represents elevation of river surface in feet where indicated topographic elevation contours cross it. Horizontal scale is distance in miles along mid-line course of stream, measured upstream from point where detailed profile was begun (variously at stream mouth, state line, or point downstream from lowest gradient anomaly).

3. River gradient profiles for Piedmont rivers in northern and central Virginia. Dark gray shaded areas are underlain by Triassic-Jurassic rocks in Newark Supergroup basins. TFL = Tidewater Fall Line, CPFL = Central Piedmont Fall Line, BRFL = Blue Ridge Fall Line. River locations are shown in Figure 1. Triangular wedges along profiles represent dams and lakes. Profiles were compiled from U.S. Geological Survey 7.5-minute topographic maps (scale 1:24,000). Vertical scale represents elevation of river surface in feet where indicated topographic elevation contours cross it. Horizontal scale is distance in miles along mid-line course of stream, measured upstream from point where detailed profile was begun (variously at stream mouth, state line, or point downstream from lowest gradient anomaly).

4. River gradient profiles for Piedmont rivers in southeastern Virginia and eastern North Carolina. TFL = Tidewater Fall Line, NFL = Nutbush Fall Line, DFL = Durham Fall Line, CPFL = Central Piedmont Fall line, **ifz** = isolated fall zone not referable to any named trend. River locations are shown in Figure 1. Triangular wedges along profiles represent dams and lakes. Profiles were compiled from U.S. Geological Survey 7.5-minute topographic maps (scale 1:24,000). Vertical scale represents elevation of river surface in feet where indicated topographic elevation contours cross it. Horizontal scale is distance in miles along mid-line course of stream, measured upstream from point where detailed profile was begun (variously at stream mouth, state line, or point downstream from lowest gradient anomaly).

5. River gradient profiles for westward flowing streams from the Blue Ridge Province that flow into the Tennessee River. GSFL = Great Smoky Fall Line. The gradient anomaly at about mile 260, at the western edge of the Nashville dome, remains unexplained. Location of the French Broad River segment of this system is shown in Figure 1. Triangular wedges along profiles represent dams and lakes. Profiles were compiled from U.S. Geological Survey 7.5-minute topographic maps (scale 1:24,000). Vertical scale represents elevation of river surface

in feet where indicated topographic elevation contours cross it. Horizontal scale is distance in miles along mid-line course of stream, measured upstream from point where Tennessee River enters the Ohio River.

6. River gradient profiles for northwestward flowing streams from the Blue Ridge Province that flow into the Kanawha River. GSFL = Great Smoky Fall Line. The gradient for the Teays River (dashed line) reflects a pre-Wisconsinan river that was destroyed by the Wisconsinan glacial ice sheet; its remaining upstream drainage now flows into the modern Ohio River. Much of the gradient anomaly represented by the New River gorge probably is due to this capture, and the rest of the gradient anomaly may be due to an earlier (Illinoisan?) disruption of the stream system. New River location in Virginia and North Carolina is shown in Figure 1. Triangular wedges along profiles represent dams and lakes. Profiles were compiled from U.S. Geological Survey 7.5-minute topographic maps (scale 1:24,000). Vertical scale represents elevation of river surface in feet where indicated topographic elevation contours cross it. Horizontal scale is distance in miles along mid-line course of stream, measured upstream from point where Kanawha River enters the Ohio River.

7. River gradient profile for the northward flowing North Fork of the Shenandoah River in the Great Valley of the Valley and Ridge Province of Virginia and West Virginia. Note that there is only one gradient anomaly along the course of this entire river. BRFL = Blue Ridge Fall Line. River location in Virginia is shown in Figure 1. Profile was compiled from U.S. Geological Survey 7.5-minute topographic maps (scale 1:24,000). Vertical scale represents elevation of river surface in feet where indicated topographic elevation contours cross it. Horizontal scale is distance in miles along mid-line course of stream, measured upstream from point where Shenandoah River enters the Potomac River.

8. Location of major fall lines in and bounding the Piedmont and Blue Ridge provinces of North Carolina and Virginia. The Atlantic Coastal Plain lies east of the Tidewater Fall Line and south of the dashed line. Black irregular ellipses mark individual fall zones along major rivers and creeks. Light-gray region denotes the eastward gravity rise shown in Bollinger and Wheeler (1988, fig. 19), and the darker-gray areas are early Mesozoic rocks filling Newark Supergroup rift basins. The dotted line along the western border of the Newark Supergroup basin in northern Virginia (the Culpeper basin), which crosses that basin in its southern area and merges into the Central Piedmont Fall Line, marks a geomorphic break in that area (the Stevensburg scarp) that indicates tectonic movement recent enough to still be reflected in the modern landscape yet too old to still disrupt the stream gradients in that area (Weems, 1993). Locations of known late Cenozoic faults are shown by open circles (data from Prowell, 1983; Pavlides and others, 1983, and Johnson and others, 1987).

9. Vertical profiles of stream gradients that cross the eastward-descending fall lines in the Piedmont of Virginia and North Carolina. Streams are located on the horizontal scale relative to each other according to their spacing (in miles) along the inner edge of the Atlantic Coastal

Plain, with 0 miles being the point where the Potomac River crosses the Coastal Plain at Washington, D.C. Vertical scale is the elevation of the river surface in feet above sea level. Low gradient regions (which are generally quite long) are shown in white, and short steep gradient areas (fall zones) are shown in gray. The diagram is designed to provide an abstracted, west-facing, end-on view of all of the major regional rivers with the height of the gray areas reflecting the total height of each fall zone along each river from the base of each fall zone to its top (marked by black dots). Heights of the various fall zones are derived from the profile anomalies marked in Figures 2 through 4. Lines between dots suggest the magnitude of vertical tectonic offset that would be required to produce the presently existing fall zones. The vertical offset along the length of each fall line changes from northeast to southwest. In general, the more westerly (inland) fall lines rise toward the southwest, while the more easterly (seaward) fall lines rise toward the northeast. The approximate elevation of the inland edge of the late Miocene and mid-Pliocene terrace deposits along the Tidewater Fall Line also are shown. State boundaries are distorted to better accommodate the intricacies of the stream patterns.

10. Relationship between Pliocene terrace sand and gravel deposits along the Staunton and Roanoke rivers and the gradient of those rivers. Dashed line marks the top of each of three well developed terrace gravel packages that have been traced by the author from the Tidewater Fall Line (right end of dashed lines in vicinity of mile 10) upriver to the vicinity of Altavista (left end of dashed lines in vicinity of mile 165). A fourth older terrace, probably of late Miocene age, is represented by a few isolated deposits. Each terrace deposit merges eastward into a regionally developed Coastal Plain terrace unit. B = river gravels that merge into the Bacons Castle formation, C = river gravels that merge into the Chowan River formation, and D = river gravels that merge into the Duplin formation. Duplin beds are about 2.8 million years old, and Chowan River beds are about 2.5 million years old. Bacons Castle beds are not directly dated, but their stratigraphic position suggests that they are latest Pliocene in age or about 2 million years old.

11. Location of inselbergs in the Piedmont of North Carolina and Virginia (adapted from Kesel, 1974), showing their relationship to the Piedmont fall lines. Note that the Central Piedmont Fall Line in Virginia and the Durham Fall Line in North Carolina mark the eastern extent of all but two of these features. The position of the Stevensburg scarp in northern Virginia also is shown.

12. Topographic profile from the vicinity of Blacksburg to the vicinity of Richmond across the southern Piedmont of Virginia, adapted from Fonseca and Vaughan (1991). Profile shows the relatively abrupt down-stepping toward the east of topography across the Blue Ridge Fall Line and the Central Piedmont Fall Line. Although the dashed line across the Western Piedmont Uplands lies on top of inselbergs, the plateau surface beneath this line follows the same slope. Although a line could be drawn from the crest of the Blue Ridge across the crest of Paris Mountain and Cloyds Mountain, the absence of any residual mantle from an ancient weathering profile on the latter two peaks indicates that any ancient plateau surface that might

once have been present across this area has been destroyed by erosion. Therefore, the slope of the top of the Blue Ridge is projected westward above those peaks, and the landscape west of the Blue Ridge is considered to be presently in dynamic equilibrium with erosion. Profile has a vertical exaggeration of 21 and was constructed at a horizontal scale of 1:1,267,200 (1 inch = 20 miles). Map below shows location of cross section.

FIGURE 1

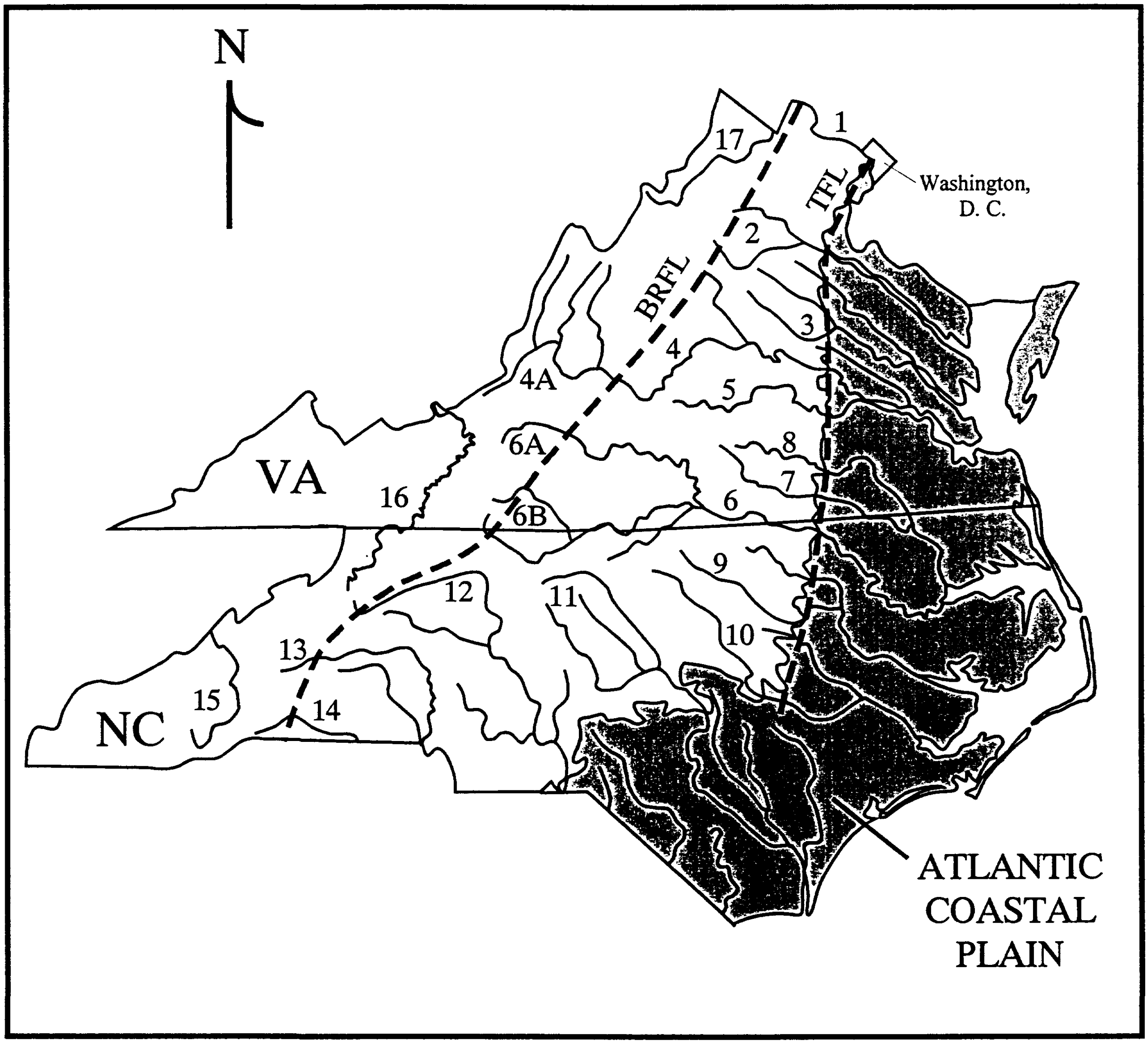
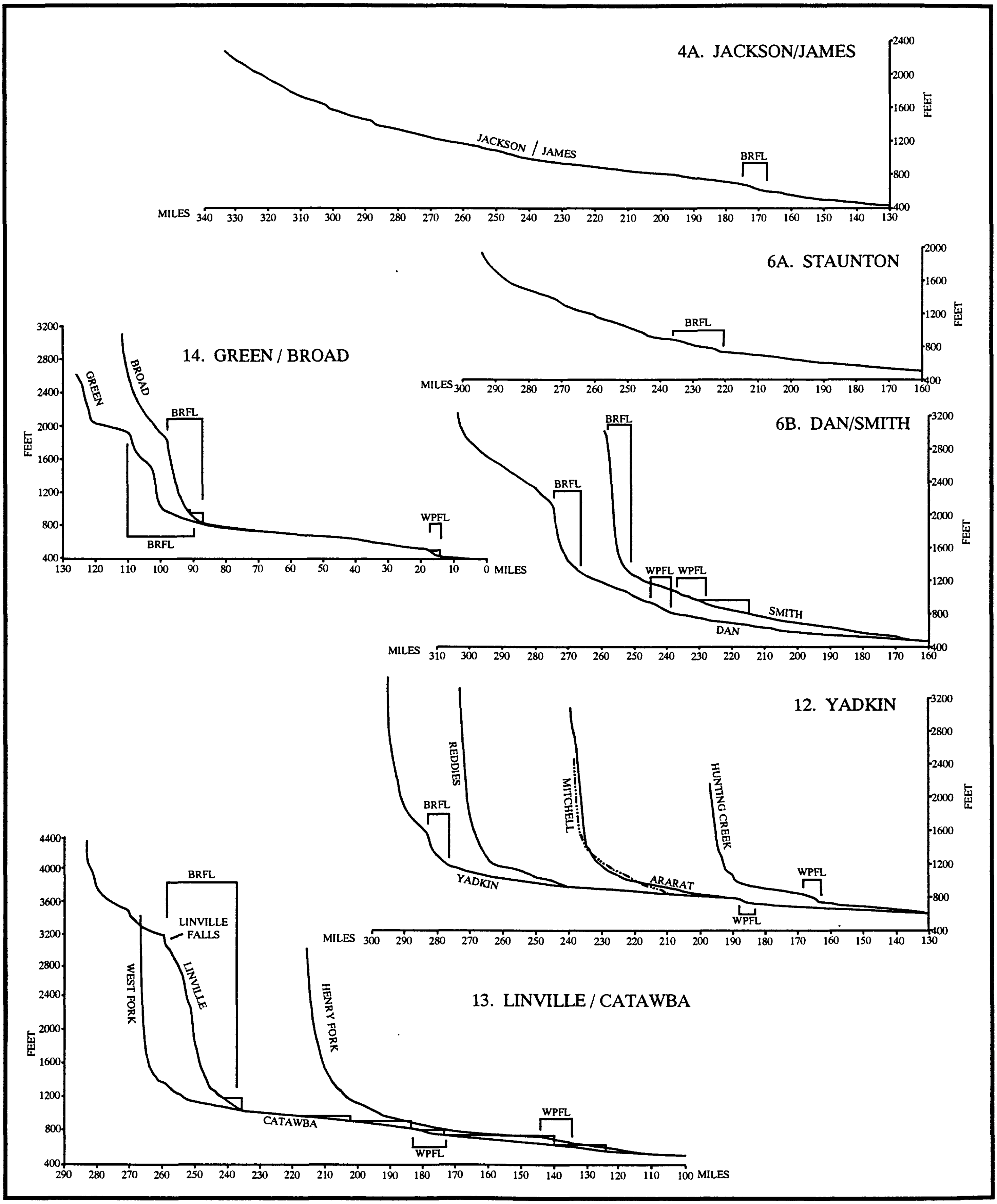
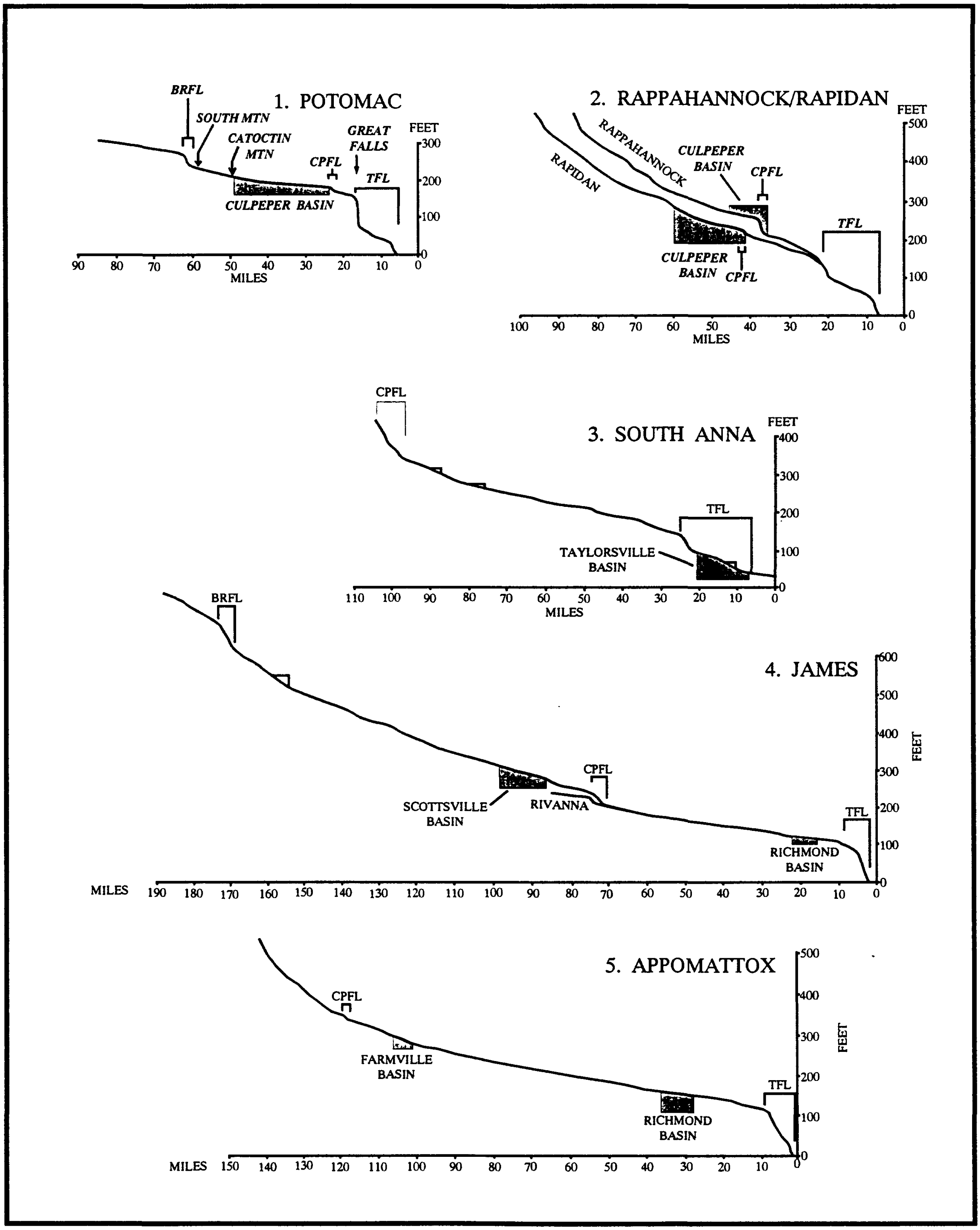

N
1
17
Washington, D. C.
TFL
BRFL
2
3
4
4A
5
6A
8
7
VA
16
6B
6
9
12
11
10
13
15
14
NC
ATLANTIC COASTAL PLAIN

FIGURE 2



4A. JACKSON/JAMES
JACKSON / JAMES
BRFL
FEET
MILES
6A. STAUNTON
BRFL
FEET
MILES
14. GREEN / BROAD
GREEN
BROAD
BRFL
WPFL
FEET
MILES
6B. DAN/SMITH
BRFL
WPFL
SMITH
DAN
FEET
MILES
12. YADKIN
REDDIES
MITCHELL
HUNTING CREEK
ARARAT
YADKIN
BRFL
WPFL
FEET
MILES
13. LINVILLE / CATAWBA
BRFL
LINVILLE FALLS
WEST FORK
LINVILLE
HENRY FORK
CATAWBA
WPFL
FEET
MILES



1. POTOMAC
BRFL
SOUTH MTN
CATOCTIN MTN
GREAT FALLS
CPFL
TFL
CULPEPER BASIN
FEET
MILES
2. RAPPAHANNOCK/RAPIDAN
RAPPAHANNOCK
RAPIDAN
CULPEPER BASIN
CPFL
TFL
CULPEPER BASIN
CPFL
FEET
MILES
3. SOUTH ANNA
CPFL
TFL
TAYLORSVILLE BASIN
FEET
MILES
4. JAMES
BRFL
SCOTTSVILLE BASIN
RIVANNA
CPFL
TFL
RICHMOND BASIN
FEET
MILES
5. APPOMATTOX
CPFL
FARMVILLE BASIN
RICHMOND BASIN
TFL
FEET
MILES

FIGURE 3

FIGURE 4

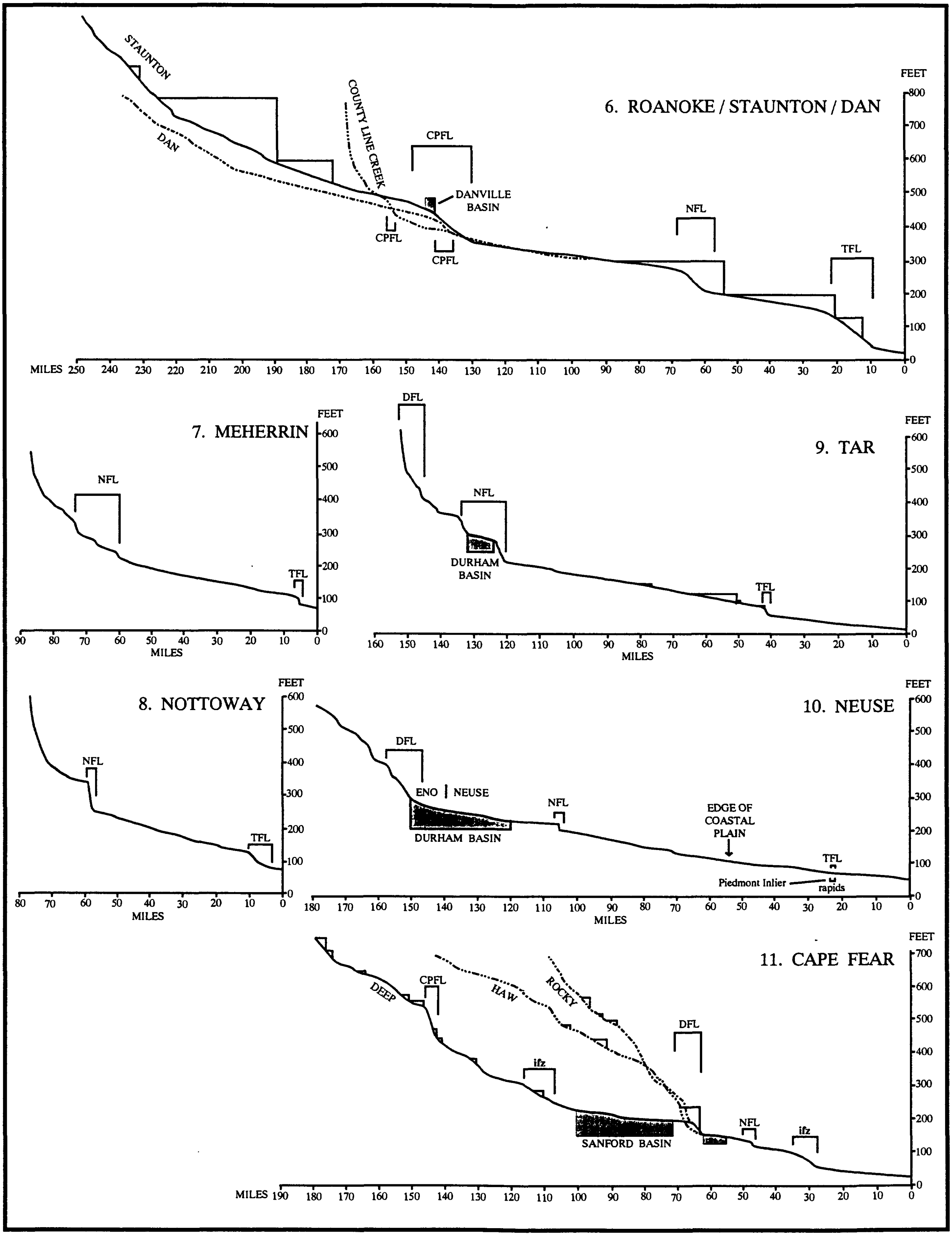

6. ROANOKE / STAUNTON / DAN
STAUNTON
DAN
COUNTY LINE CREEK
CPFL
DANVILLE BASIN
NFL
TFL
FEET
MILES
7. MEHERRIN
9. TAR
DFL
DURHAM BASIN
8. NOTTOWAY
10. NEUSE
ENO
NEUSE
EDGE OF COASTAL PLAIN
Piedmont Inlier
rapids
11. CAPE FEAR
DEEP
HAW
ROCKY
ifz
SANFORD BASIN

FIGURE 5

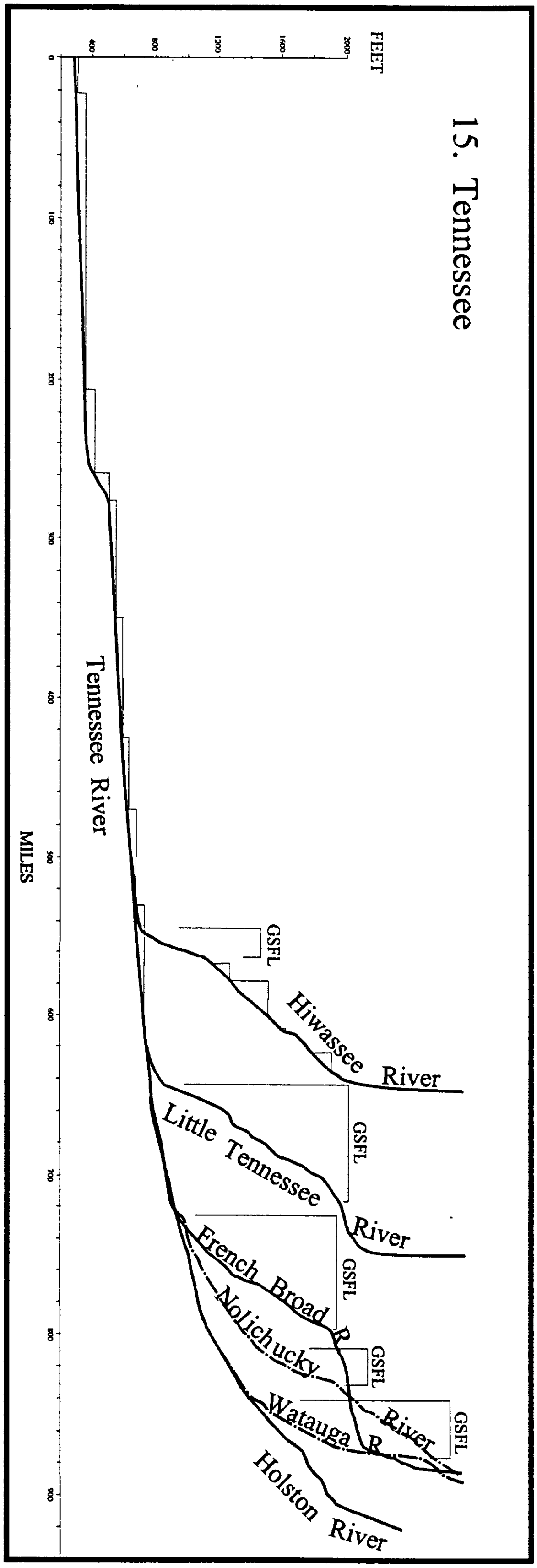
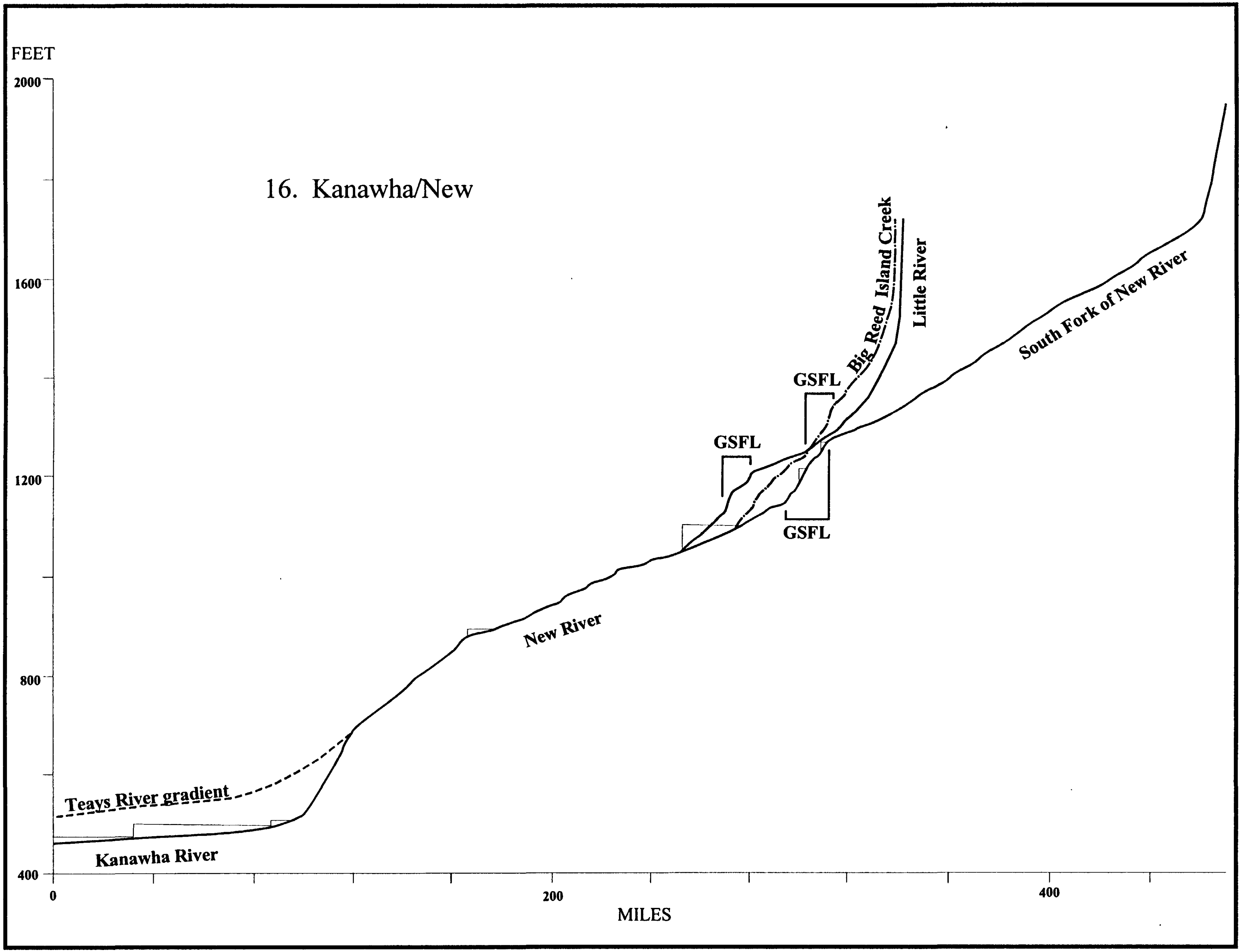
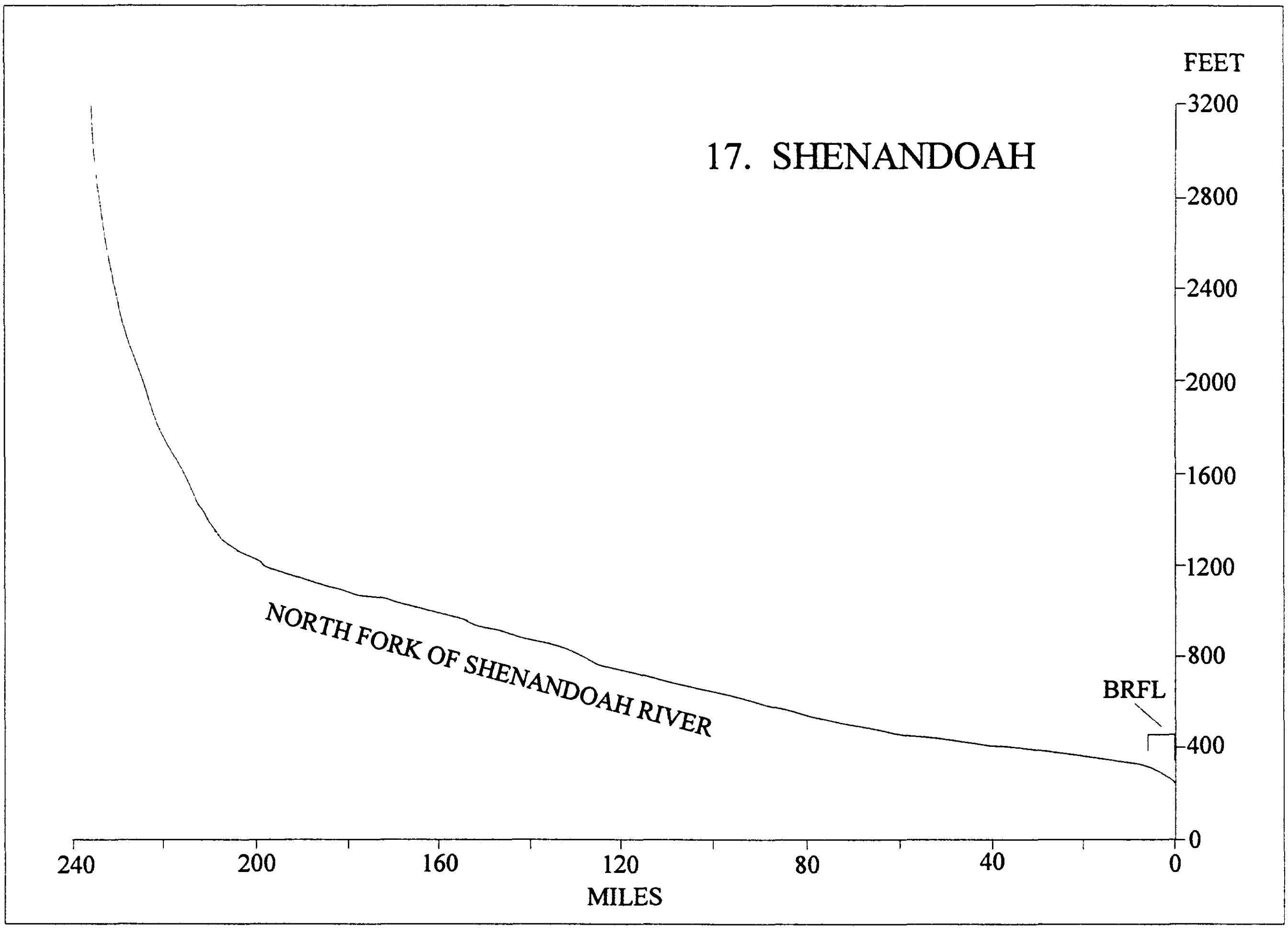

15. Tennessee
FEET
MILES
Tennessee River
Hiwassee River
Little Tennessee River
French Broad R
Nolichucky River
Watauga R
Holston River
GSFL
GSFL
GSFL
GSFL
GSFL

FIGURE 6



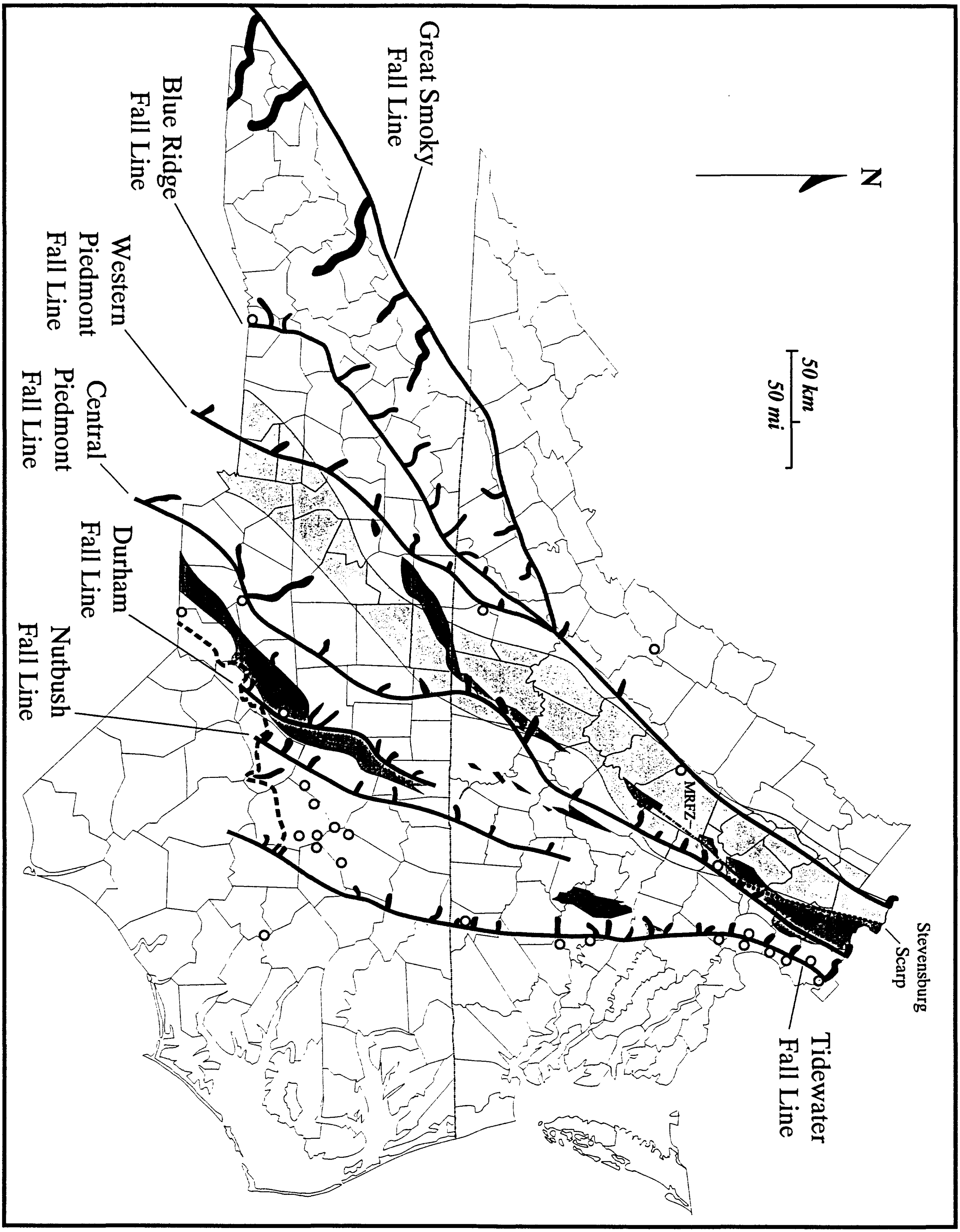
FEET
2000
1600
1200
800
400
16. Kanawha/New
Teays River gradient
Kanawha River
New River
GSFL
GSFL
GSFL
Big Reed Island Creek
Little River
South Fork of New River
0
200
400
MILES

FIGURE 7



FEET
3200
2800
2400
2000
1600
1200
800
400
0
17. SHENANDOAH
NORTH FORK OF SHENANDOAH RIVER
BRFL
240
200
160
120
80
40
0
MILES

FIGURE 8



Great Smoky Fall Line
Blue Ridge Fall Line
Western Piedmont Fall Line
Central Piedmont Fall Line
Durham Fall Line
Nutbush Fall Line
Tidewater Fall Line
Stevensburg Scarp
MRFZ
N
50 km
50 mi

FIGURE 9

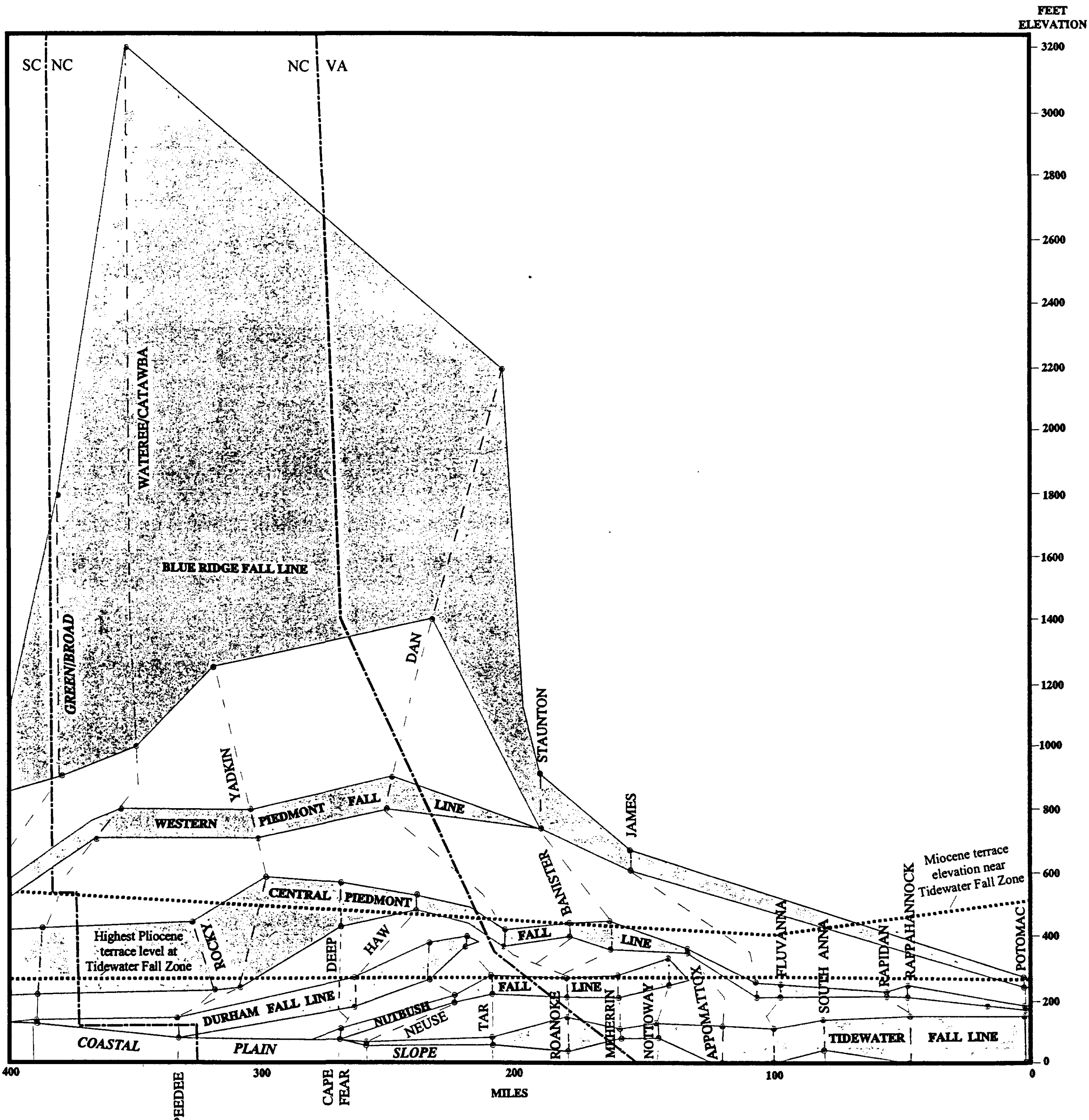

FEET ELEVATION
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
SC NC
NC VA
WATEREE/CATAWBA
GREEN/BROAD
BLUE RIDGE FALL LINE
DAN
STAUNTON
YADKIN
WESTERN PIEDMONT FALL LINE
JAMES
BANISTER
Miocene terrace elevation near Tidewater Fall Zone
CENTRAL PIEDMONT
Highest Pliocene terrace level at Tidewater Fall Zone
ROCKY
DEEP
HAW
FALL LINE
FLUVANNA
SOUTH ANNA
RAPIDAN
RAPPAHANNOCK
POTOMAC
DURHAM FALL LINE
NUTBUSH
NEUSE
TAR
ROANOKE
MEHERRIN
NOTTOWAY
APPOMATTOX
FALL LINE
TIDEWATER FALL LINE
COASTAL PLAIN SLOPE
400
300
200
100
0
MILES
PEEDEE
CAPE FEAR

FIGURE 10

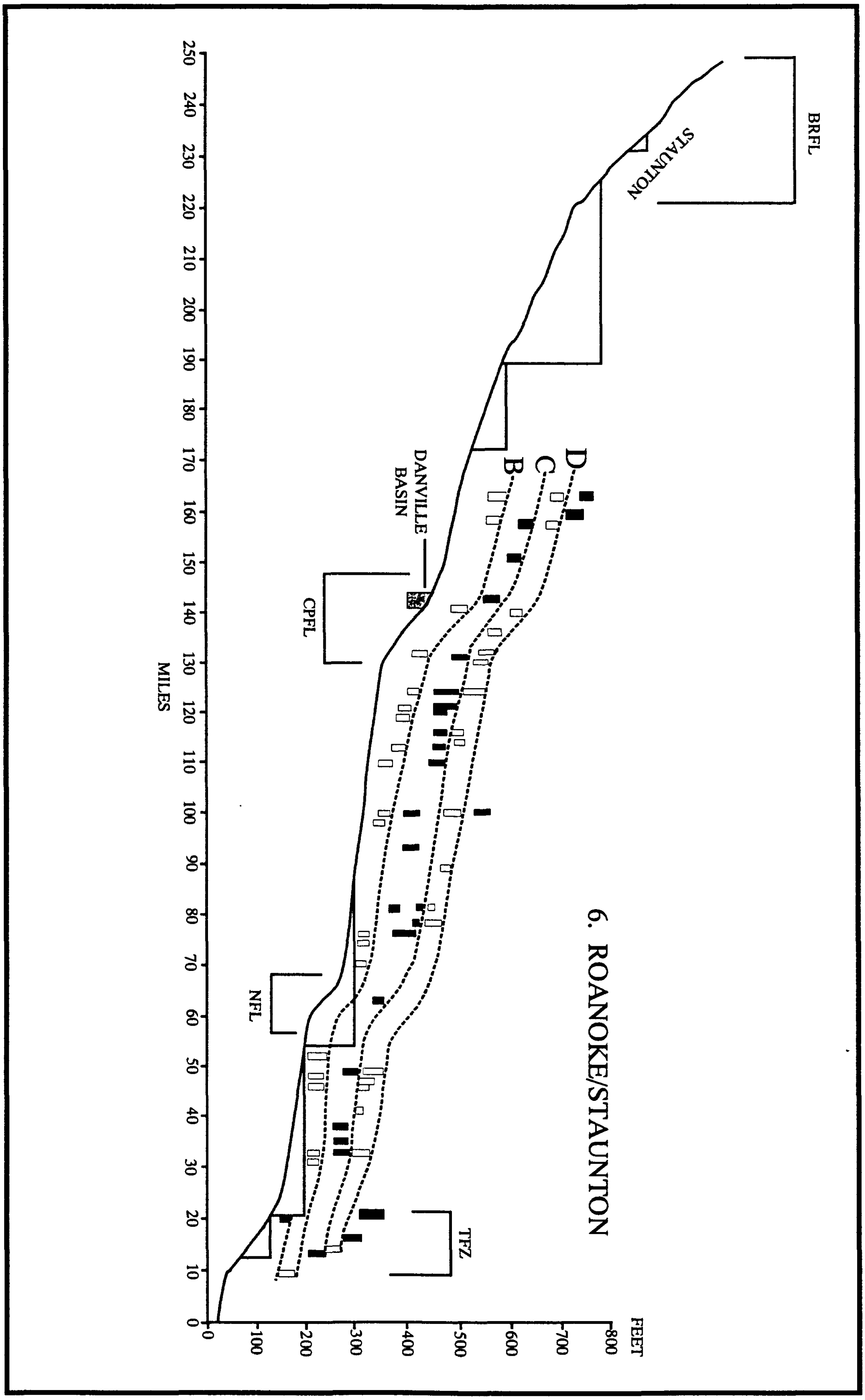
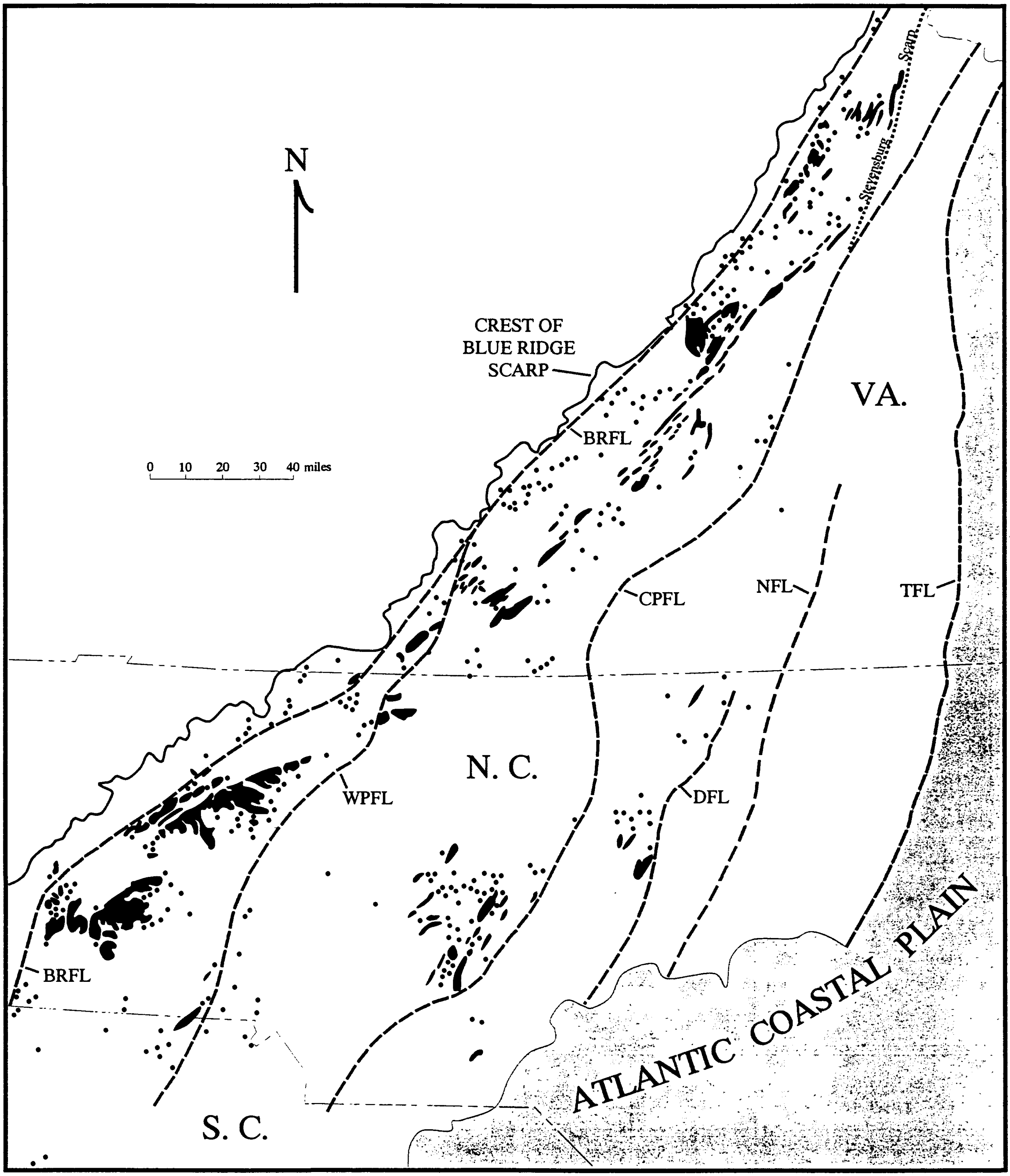
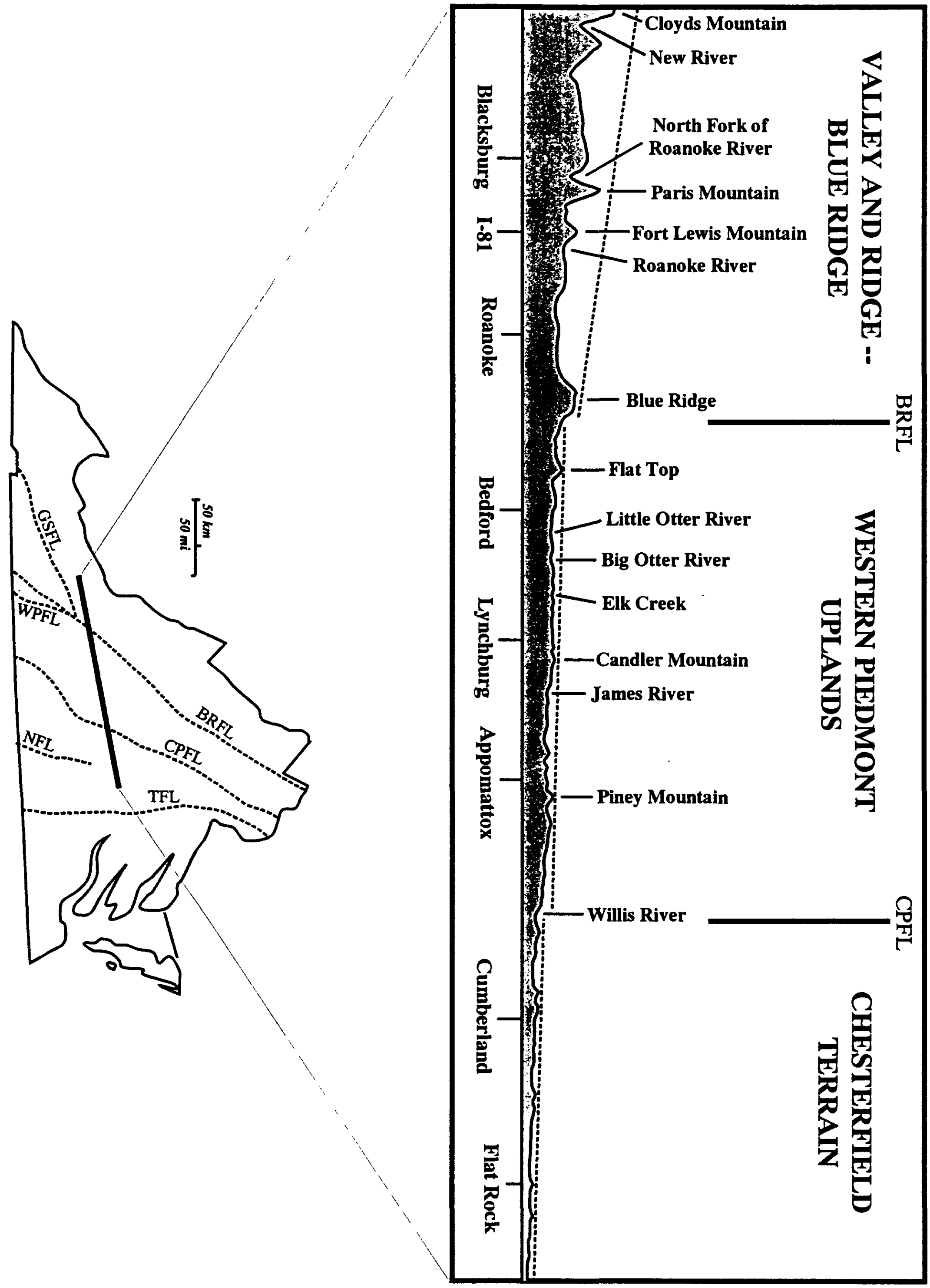

6. ROANOKE/STAUNTON
BRFL
STAUNTON
D
C
B
DANVILLE BASIN
CPFL
NFL
TFZ
MILES
FEET
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
100
200
300
400
500
600
700
800

FIGURE 11



N
0 10 20 30 40 miles
CREST OF
BLUE RIDGE
SCARP
BRFL
Stevensburg
Scarp
VA.
CPFL
NFL
TFL
N. C.
WPFL
DFL
BRFL
ATLANTIC COASTAL PLAIN
S. C.

FIGURE 12



Cloyds Mountain
New River
North Fork of Roanoke River
Paris Mountain
Fort Lewis Mountain
Roanoke River
Blue Ridge
Flat Top
Little Otter River
Big Otter River
Elk Creek
Candler Mountain
James River
Piney Mountain
Willis River
VALLEY AND RIDGE -- BLUE RIDGE
BRFL
WESTERN PIEDMONT UPLANDS
CPFL
CHESTERFIELD TERRAIN
Blacksburg
I-81
Roanoke
Bedford
Lynchburg
Appomattox
Cumberland
Flat Rock
50 km
50 mi
GSFL
WPFL
BRFL
NFL
CPFL
TFL