ESSENTIAL QUESTIONS TO ASK

Atlantic Southeast.1 Introduction

- *Why aren't active volcanoes present within the Atlantic Southeast region despite a record of seismic activity?*
- *How has the geology of the Atlantic Southeast region contributed to the economic history of the United States?*

Atlantic Southeast.2 Proterozoic Geology and Tectonics

- *What events led to the formation of Rodinia?*
- *What evidence exists for interpreting a continental rifting event along the margin of Laurentia in the Late Proterozoic?*

Atlantic Southeast.3 Late Proterozoic Climates, Paleogeography, and Life

- *What is the significance of glacial climates in both Laurentia and peri-Gondwanan exotic terranes during the Late Proterozoic?*

Atlantic Southeast.4 Early Paleozoic History of the Laurentian Continental Margin

- *What was Iapetus, and where was it located?*
- *How do the Early Paleozoic strata of the Laurentian continental margin differ from the underlying Late Proterozoic stratified rocks?*

Atlantic Southeast.5 Proterozoic and Early Paleozoic History of the Terranes Comprising the Piedmont

- *How does the geologic history of an exotic terrane that existed within the Iapetus Ocean marginal to Gondwana differ from that of Laurentia?*
- *What evidence exists that demonstrates the size of Iapetus?*

Atlantic Southeast.6 Middle Ordovician through Late Paleozoic Geology and Tectonics

- *What events comprise the Taconic Orogeny?*
- *What events comprise the Acadian Orogeny?*
- *What events comprise the Alleghanian Orogeny?*

Atlantic Southeast.7 Mesozoic and Cenozoic Geology and Tectonics

- *What is a rift-to-drift sequence?*
- *Why do some rift basins have strata dipping northwest while others have strata dipping southeast?*

Atlantic Southeast.8 Natural and Anthropogenic Hazards of the Atlantic Southeast Region

- *What current natural hazards facing the population of this region today pose the greatest threats to property and life?*
- *What are the chances of Myrtle Beach, South Carolina, and Virginia Beach, Virginia, being destroyed by a catastrophic tsunami?*

Atlantic Southeast.1 Introduction

The Atlantic Southeast region (Figure 1) is a fundamental region not only for learning and understanding the history and growth of the United States but also because many classical ideas of geology originated from studies of rocks, soils, rivers, beaches, and other processes in this region. The eroded southern remnants of the Paleozoic **Appalachian orogenic belt** dominate the western two thirds of the region, and the overlapping, essentially horizontal strata and fringing barrier islands of the Coastal Plain occupy the eastern third. The extensive fluvial and estuary systems of the Coastal Plain provided transportation routes and protected harbors for the ships bringing early explorers and colonists to the region during the seventeenth century. The extensive beaches of the Coastal region continue to play an important role for tourism in addition to the rich history and natural beauty found there. The natural beauty and attractions of the current geography are better understood as the products of balanced geologic processes that have occurred repeatedly through time.

The Appalachian region provided the central framework for the concept of geosynclines as proposed by James Hall and J. D. Dana in the 1800s. Hall noticed that Paleozoic limestone strata in the central region of North America were thicker in the Appalachians even though all of the limestone layers originally accumulated in shallow waters. The correct explanation for this paradox is for the floor of the basin to gradually subside at a pace that kept the uppermost sedimentary layer within shallow water. This realization of a mobile crust fostered new thinking that linked various observations of geologic processes into a logical explanation for linear basins containing vast thicknesses of sediments. Hall and many of those who followed used Appalachian stratigraphy to link sedimentation, sedimentary facies, volcanism and plutonism, folding, faulting, metamorphism, and even crustal growth by outward accretion of geosynclines to ancient cratons. Plate tectonics supplanted geosynclinal theory in the late 1960s, but the basic concept of a mobile crust is a fundamental root of the newer tectonic concepts. Whereas geosynclines stressed vertical motions within the crust, plate tectonic theory demonstrates the equal, if not more dominant, role of horizontal displacements of continental and oceanic crust and underlying lithosphere in explaining the way that the Earth works. The Appalachian region was one of the first mountain systems to be explained in terms of plate tectonic theory. The Atlantic Southeast region provides an excellent opportunity to study the complete historical cycle of the Appalachians from beginning to end (see Frontispiece Geologic Map). The region also permits a chance to evaluate more recent effects of Cenozoic climate change on coastal margins and may provide guiding insights into the future chapters of geologic history.

Current Tectonic Setting

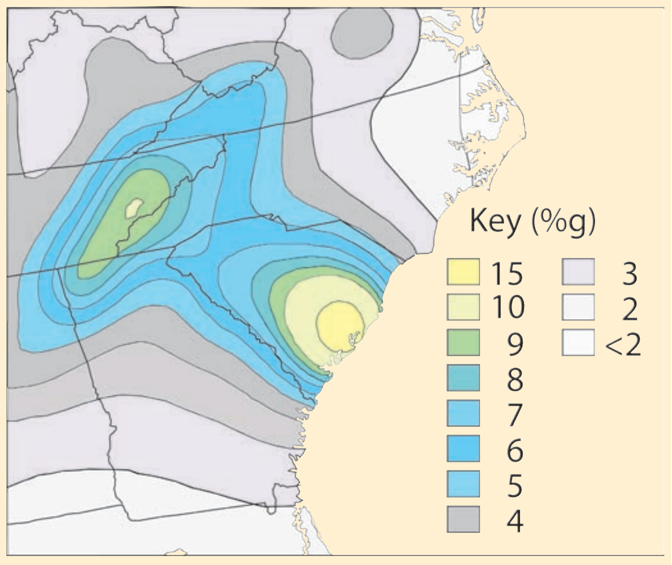
The Atlantic Southeast region currently is classified as a passive continental margin. When a large continent splits, smaller fragments begin drifting apart. **Passive margins** occur along the trailing edge of drifting continents and border ocean basins that expand with increasing separation of the continents. Passive margins lack any of the major earthquake and magmatic activity that is so prevalent at the leading edges of drifting continents at convergent plate boundaries. Earthquake activity does occur in passive margins, but the frequency of major events is very low and magnitudes are not catastrophic. The seismic activity results from interactions between consistent horizontal compressive stresses and older structures such as faults, **shear zones**, or plate boundaries. Over time, the older structure moves slightly to relieve the accumulating pressure from the applied stresses. During the evening of August 31, 1886, near Charleston, South Carolina, an earthquake with an estimated Richter magnitude exceeding 7.0 created widespread damage in the Charleston area, including the deaths of some 60 people. This is the only known major earthquake to have affected the southeast region in recorded history. A few moderate earthquakes have occurred in an area extending through eastern Tennessee and into southeastern West Virginia with Richter magnitudes less than 5.5, much lower than the Charleston earthquake. Even so, the U.S. Geological Survey (USGS) predicts that part of the Atlantic Southeast region may experience moderately low to moderate seismic activity within the next 50 years (Figure 2).

Present-Day Natural Hazards

The significant threats to life and property in the Atlantic Southeast region stem from natural hazards related to tropical storms. The region borders the southeastern Atlantic

► **Figure Atlantic SE.1** Physiographic provinces in the Southern Appalachians. Boundaries are approximate. Base digital elevation map: U.S. Geological Survey.

Figure Atlantic SE.2 Potential for seismic hazards within the next 50 years. Peak acceleration values listed in percentage of gravitational acceleration (% g).



U.S. Geological Survey

Basin, where many historical events of major hurricanes and nor'easters abound.

Coastal storms and hazards recur at frequent intervals and cause much destruction of property from severe coastal erosion, high winds, extensive flooding, and even significant mass wasting in mountainous regions located far from the direct landfall of the storm.

Resource Potential

The Atlantic Southeast region has a long history of production of ore, gemstone, and industrial minerals that have had significant economic significance to the United States. All of these resources originated with appropriate tectonic events comprising the geologic history of the southern Appalachians. Discovery of gold in 1799 in the central Piedmont of North Carolina led to exploration, discovery, and eventual production of different metallic resources including gold, silver, copper, lead, and zinc. Current interests for discovering additional metallic mineral deposits in the Piedmont region of the Carolinas will probably discover more deposits, but high volumes of ore are not expected. In addition to base and precious metallic ores, iron-rich sedimentary rocks within the Valley and Ridge and Blue Ridge became valued commodities because of their ready access to nearby rivers for ready smelting and transportation. A few forges remain as interesting historical markers to this history. These old iron-works dating back to early colonial history provided raw materials for use in local manufacturing of finished products including farm and household equipment and tools, rims for wagon wheels, and gun barrels and other weapons.

Nonmetallic resources are produced in much greater quantities than metallic mineral resources in the region. The Blue Ridge and Piedmont areas are renowned for their gem minerals including emeralds, rubies, sapphires, and diamonds. The most significant resources, though, are dimension stone and other industrial rocks and minerals. The largest open-faced **granite** quarry in the world can be seen at Mount Airy, North Carolina. Stone quarried today from the quarry perfectly matches stone extracted 100 years ago because of the prized aspect of Mount Airy granite's homogeneous fabric and texture. This stone is in high demand for use in monuments and other less glamorous applications such as curbstones in cities including Boston, New York, and Washington, DC. North Carolina also ranks as the number one source of olivine, a mineral critical for manufacturing high-temperature furnaces for smelting other metals and making alloys.

Geologic processes of weathering, erosion, and transportation of sediment provided necessary steps in forming several natural resources within the Coastal Plain, including sand and gravel deposits (valued for high-grade silica extraction and use in construction), phosphate (important ingredient for fertilizers), and even placer deposits of heavy minerals (important sources of metals used in producing alloys, as well as gold and minerals used for making abrasives).

Energy resources available in the southeast region include lignite, coal, oil, and natural gas. Bituminous coal fields occur throughout the later Paleozoic sedimentary rocks of the Appalachians. Peat and lignite deposits of the Coastal Plain are hydrocarbon resources for energy and other uses. The world's first successful well drilled to find oil was in the Appalachians, and the Paleozoic strata of the southern Appalachians continue to have significant production of both oil and natural gas. Limited studies and exploratory investigations suggest the potential of hydrocarbon resources offshore in the coastal waters of the continental shelf. Existing legislation bans these tracts from detailed exploration and prevents any significant evaluation of their real potential.

Our understanding of the geology and geologic history of the Appalachians helps us understand the interrelations among geologic processes, mineral and rock deposits, and even hydrologic resources. We can make realistic predictions about the future availabilities of resources that are vital to the health and welfare of our nation. Geologic efforts also enable us to find better solutions to environmental concerns demanding assessment and evaluation. The best way to plan for the future of this historically important area is to study the geologic past and understand its changes through time.

A Note on Physiographic Subdivisions

Physiography is the study of landforms and other physical features of the Earth's surface. Processes of physical and chemical weathering, erosion, and deposition modify landscapes that are very rugged with high relief to those that are very subdued with low relief. Internal geologic characteristics of rocks in differing geographic areas produce distinctive features that lead to natural groupings of similar landforms, or physiographic subdivisions. In the Appalachians, physiographic subdivisions have always provided a useful, convenient scheme for discussing the geology, a tradition continued here (see Figure 1). From west to east, the region consists of folded and faulted sedimentary rocks of the Plateaus and Valley and Ridge, the igneous and metamorphic rocks of the Blue Ridge and Piedmont, and the eastward-thickening wedge of younger subhorizontal strata of the Coastal Plain.

Atlantic Southeast.2 Proterozoic Geology and Tectonics

The geologic history of the Atlantic Southeast region begins during an ancient interval of geologic time known as the Proterozoic Eon. The compilation of the geologic time scale itself is an excellent example of using the logic of science to piece together many scattered tidbits of information into a useful tool. Major or mega blocks of time lasting several hundred to several hundreds of millions of years are called eons. Successively smaller intervals of times are eras, periods, and epochs, respectively. In studying rocks that are older than approximately 600 million years, geologists rely heavily on using isotope-dating techniques for deciphering a time sequence in these metamorphic and igneous rocks. The Proterozoic Eon spanned approximately 2 billion years of Earth history before the dawn of the present Phanerozoic Eon and its fossil-bearing rocks. Many geologists recognize that an important and fundamental transition in the way that the Earth works occurred during the Proterozoic. Active and relatively rapid geologic processes operating with thin crusts, small continents, and small ocean basins characterize geologic workings of the earlier Archean Eon. The more stable and slower geologic processes of the current Phanerozoic Eon reflect the increasing stability that progressively accumulated during the Proterozoic through cooling and thickening of the continental crust within a tectonic framework similar to that of today. A stable continental crust is thick enough to slow down the transfer of heat from the Earth's mantle the Earth's surface. As a thicker crust reduces the flow of heat, then less thermal energy is available to create quick and large uplifts with rapid tectonic activity in the continental interiors. Stability allows continents to increase their surface area exposed to surface processes over long periods. In turn, more effective weathering and efficient erosion results in deposition of mature sediments within large, established sedimentary basins. Although the Proterozoic contains tracks of immature sedimentary rocks mixed with extensive volumes of volcanic rocks that characterize typical rocks of the Archean Eon, such assemblages are less extensive and are separated by broad regions of relatively undisturbed, quiet water sediments unaffected by significant magmatic or tectonic activity. The marked increase in stability of Proterozoic continental crust enables us to use present-day

▶ Figure Atlantic SE.3 Sketch map of Rodinia with composite continents.

geologic characteristics and processes associated with plate margins as guides for interpreting the geologic history of the oldest rocks existing within the Atlantic Southeast region.

Metamorphic rocks exposed in northeastern Tennessee and northwestern North Carolina are approximately 1.8 billion year old, forming originally as sedimentary and igneous rocks associated with a large and stable continent known as **Laurentia**. Similar and slightly younger rocks comprise an axial zone within the Blue Ridge that compares favorably with rocks along the eastern and southeastern margin of Laurentia known as the **Grenville** Province. Geologists interpret the Grenville rocks as the products of a series of tectonic events associated with collisions between eastern Laurentia and ancient smaller continents that now probably exist within South America and Australia. The collisions spanned an interval of approximately 200 million years (1.2–1.0 billion years) and were part of a process that assembled the supercontinent **Rodinia** (Figure 3). The Atlantic Southeast provides some insights into this construction.

Geologists know virtually nothing about the intervening ocean basin consumed by the collisions between eastern Laurentia and the approaching continents. Exposures of Grenville-aged rocks along the Blue Ridge (Figure 4) support an interpretation of colliding continents driven over the edge of Laurentia in the same manner that Asia currently overrides northern India in the Himalaya Mountains. The larger size and greater thickness of Proterozoic continents generated large, compressive stresses during the collisions that extended to great depths. The combination of large stresses and higher temperatures at depth along the edges of the colliding continents resulted in deforming rocks at elevated temperatures, a major requirement for high-temperature and high-pressure regional metamorphism.

Figure Atlantic SE.4 Exposure of Grenville basement rock near Mars Hill, North Carolina. Darker layers of biotite-hornblende gneiss and lighter layers of biotitic granite gneiss.

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Part of the horizontally directed compressive stress cut through the rocks, creating tabular, thick masses along zones of ductile shearing (mylonite zones). Eventually, blocks of lower crustal rocks thrust forward and upward along the mylonite zones to shallower depths within the crust. The progressive deformation squeezed the continental crusts involved in the collision into narrower intervals by telescoping the lower and upper parts of the crusts into thicker, vertically stacked layers of higher-grade metamorphosed rocks on top of lower-grade, shallow crustal rocks, including sedimentary rocks characteristic of stable continental margins. The collision process generated heat through friction and decompression that resulted in partial melting and subsequent widespread intrusive activity that welded the zone of collisions to Laurentia as part of the formation of the much larger Rodinian supercontinent.

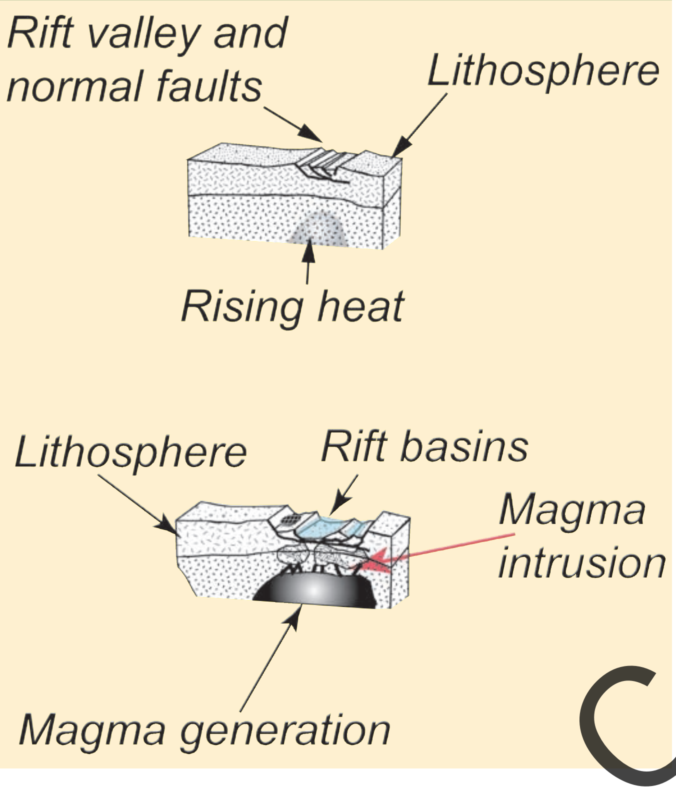
Grenville-aged rocks in the Atlantic Southeast region occur either as elongated masses of metamorphosed plutonic rocks within the axial region of the Blue Ridge or as isolated, domelike masses surrounded by younger rocks within the Piedmont. Although these rocks possess distinctive remnant evidence of their Grenville history, their current geologic and geographic positions record a complex history of younger, overprinting, non-Grenville tectonic events. Grenville-aged rocks of the Blue Ridge and Piedmont are fragments of Rodinia that rifted apart from the supercontinent during the late Proterozoic. Similar fragments are found in other continents that drifted apart with the disaggregating of Rodinia. Some of the larger fragments now comprise a group of Laurentian continents; the remainder constitutes the Gondwanan continents. Smaller fragments of Rodinia existed as independent land masses (**microcontinents**) fringing the peripheral margins of both Laurentian and Gondwanan continents and produced similar, but not identical, geologic histories. Ironically, much younger geologic and tectonic events consolidated the rifted fragments back into Laurentia during the assembly of the next supercontinent, **Pangaea**.

Late Proterozoic Geologic History

Continental rifting typically follows the final consolidation of a supercontinent. Metamorphosed sedimentary and related igneous rocks of the Blue Ridge in Virginia, North Carolina, and Tennessee are relics of active continental rifting within Rodinia approximately 750 million years ago during the Late Proterozoic. Linear basins bordered by normal faults opened within the crust and began filling with a very thick volume of rapidly deposited sedimentary rocks. Later Paleozoic orogenic events obliterated much of the contiguous regional record for rifting of Rodinia, but careful research on selected areas in the Atlantic Southeast region reveals some aspects of this important stage in the geologic history of the Appalachians.

Rifting of a supercontinent begins with a broad circular or domelike uplift of the crust and lithosphere situated over a rising plume of asthenosphere (Figure 5). Heating of the lithosphere causes it to buoyantly rise upward. The continental crust situated at the top of the lithosphere stretches over the rising dome and begins to rupture along a three-armed pattern of major fracture zones that radiate outward from the central area of uplift. Each arm hosts a growing system of normal faults and narrow, linear, sedimentary basins within the down-dropped blocks (graben). As more separation occurs along the faults, the basins become wider and deeper. High topographic relief between the uplifted horsts of continental crust and the floors of the sedimentary basins in graben drives a rapid process of erosion and deposition that pours very coarse-grained and poorly sorted clastic sediments into the basins. Alluvial fans accumulate at the base of the steep slopes of adjacent horsts. Fluvial environments characterize the interior of the basins. Deep lakes also can form within the lowest parts of the basins. The linearity of the basins requires rapid transitions between sedimentary facies over a narrow distance. Sandstones represent the finer-grained clastic sediments of the fluvial systems and locally contain significant amounts of feldspar, mica, and other types of sedimentary and igneous rock. The fluvial facies change into mud-rich sediments of deep lakes. Interior drainage within the basins favors the formation of playa lakes and deposition of layers containing evaporite minerals (salts) interbedded within the pile of clastic sediments. Continued extension and rifting results in the floors of the basins and lakes extending to depths well below sea level. However, only two of the arms and basin systems

▶ **Figure Atlantic SE.5** Processes of continental rifting. Heat of rising plume lifts overlying continental crust and thins lithosphere. Extensional normal faults accommodate uplift and thinning. Partial melting of underlying material leads to basalt magmas that rise and intrude along channels created by fault system.

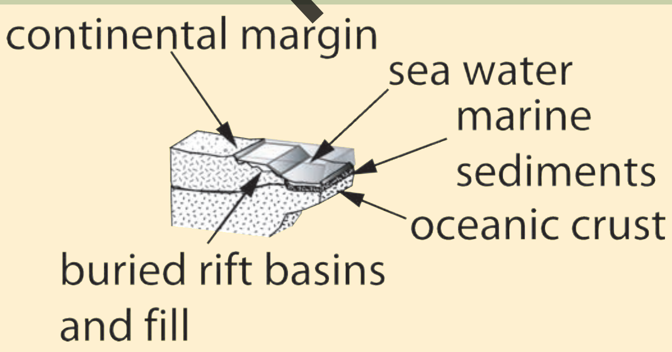


continue to grow and expand, eventually merging into a juvenile ocean basin (Figure 6). The third arm ceases to expand, but its aborted rift history can be preserved in the rock record.

The rising plume affecting the lithosphere also generates magmas that intrude the crust along rift-related normal faults. Volcanoes form with repeated eruptions, leaving a record of alternating flows of **basalt** within various levels of sediments deposited in the basins. Basalt dikes and sills also penetrate the sedimentary pile as satellite intrusions branching from the feeder system for the magma. Small plutons of alkali-enriched granitic originate within the thinned continental crust and rise to shallow depths underlying the **rift basin**. As the two favored systems of rift basins begin to merge as one, an incipient ocean basin with juvenile oceanic crust grows from the increased volume of injected basaltic magma. Through time and growth of the oceanic crust, the rift basins fringing the edge of the ocean basin gradually cool, become tectonically inactive, and subside under the growing weight of transgressing marine sediments. The buried rift valleys and their cover of fine-grained marine sediments comprise a characteristic stratigraphic package on the trailing edge of the drifting continent known as a passive margin sequence. As long as the ocean basin continues to grow by spreading from its central ridge system, the passive margin exists without major interruptions for very long time intervals of geologic time.

Late Proterozoic stratified rocks unconformably overlie Grenville basement rocks within linear basins locally bound by faults at several centers within the Blue Ridge. One extremely thick sequence, the Great Smoky Group, underlies the Great Smoky Mountains of western North Carolina and eastern Tennessee (Figure 7). Characteristic rocks of

▶ **Figure Atlantic SE.6** Establishing the passive continental margin. Continued rifting results in merging of two arms of original rift. Thinned and subsided crust of rift basin becomes flooded by surrounding sea waters. Continued subsidence occurs with cooling and progressive movement of continental margin from juvenile ocean basin.



▶ **Figure Atlantic SE.7** Folded metasandstone and schist exposed in Great Smoky Mountains National Park at Woolyback Overlook, North Carolina.

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the metamorphosed sequence include very coarse conglomerates grading into feldspathic sandstones, mudrocks and interstratified turbidite deposits, and shales deposited under less-energetic conditions. At other locations in the Blue Ridge, dikes and sills of fine-grained gabbro (known locally in North Carolina as the Bakersville) intrude Late Proterozoic rocks and represent feeder systems for layers of basalt and rhyolite found within the various successions (Grandfather Mountain and Mount Rogers Formations, for example). Small stocks of alkaline-rich granite (Crossnore group of plutons along the Blue Ridge), whose absolute ages coincide with the relative stratigraphic positions of Late Proterozoic rocks, intrude both the strata and the underlying Grenville basement along a trend that is traceable northward within the Blue Ridge from North Carolina through Virginia.

The geologic events responsible for continental rifting and associated magmatic activity often work to concentrate metallic elements into resources. Within the Blue Ridge, many old prospects and mines in both the crystalline rocks of the basement, stratified deposits, and cross-cutting plutonic rocks have yielded significant amounts of copper and iron and even precious metals including gold and silver.

Atlantic Southeast.3 Late Proterozoic Climates, Paleogeography, and Life

Late Proterozoic stratified rocks of the Blue Ridge in the Mount Rogers area of southwestern Virginia and similar rocks in the Grandfather Mountain area of northwestern North Carolina provide some interesting clues supporting the presence of continental glaciers at this time. Thick, massive units consisting of poorly sorted (boulder- to silt-sized) clasts within the uppermost parts of the Late Proterozoic strata grade into areas of mudrock consisting of alternating thin lamina of silt and clay. Some of the thinly laminated clay mudrock units contain large, somewhat angular clasts of exotic rocks including granite and rhyolite. The clasts penetrate and deform underlying lamina of clay and silt. However, the laminar stratification also envelopes the upper parts of the exotic clasts, indicating that sedimentation continued long after the introduction of the fragments in the sediment. Possible interpretations for explaining the exotic clasts as dropstones include falling ejecta from local volcanoes (for the rhyolite) and rafting of continental sediments by icebergs into meltwater lakes (for the granite). If the laminated mudrocks represent varved deposits of glacial lakes, then the massive conglomeratic units could represent glacial tillites. The paucity of additional exposures exhibiting these features leaves an open interpretation for the Blue Ridge strata as glacial deposits. No unambiguous exposures of polished and striated basement exist below the postulated glacial deposits in the Blue Ridge. Indirect support for widespread continental glaciation in the Late Proterozoic includes sedimentologic and stratigraphic interpretations from both surrounding and younger overlying strata, but the interpretation remains inconclusive. Other regions in the world yield relatively conclusive evidence of Late Proterozoic glaciation, but their stratigraphic correlation with similar-aged strata in the Blue Ridge is not well-defined and certain.

Reported discoveries of fossils in the Late Proterozoic stratified succession include visible impressions of probable multicellular organisms and microscopic fossils identified as acritarchs. The poor preservation of the indistinct impressions prevents a positive identification of these fossils to any particular type of Late Proterozoic soft-bodied organism, but little doubt exists regarding the age of the impressions. The range of time during which acritarchs lived extends from the Late Proterozoic into the Early Paleozoic. Their local occurrences within strata that correlate with known uppermost units of the Late Proterozoic succession help to constrain the age of these rocks in the Blue Ridge. Structural complexities inhibit conclusive correlations between exposures containing other reported fossil discoveries and known fossil-bearing strata in either Late Proterozoic or Early Paleozoic strata within the Blue Ridge area. Widespread, pervasive deformation and metamorphism during younger Paleozoic orogenic events, as well as erosion of potentially fossiliferous rocks obliterated most chances of discovering evidence of life in the Late Proterozoic succession of the Blue Ridge.

Atlantic Southeast.4 Early Paleozoic History of the Laurentian Continental Margin

Gondwana and its peripheral microcontinents continued to drift away from the passive eastern margin of Laurentia during the Early Paleozoic (Figure 8). Clastic sediments transported by rivers draining Laurentia entered the flooded continental shelf where currents worked to grade and sort them during their transition from a fluvial to shallow marine environment. Quiet, shallow marine waters permitted settling of suspended mud and precipitation of dissolved ions in the streams as layers of terrigenous mud and chemical sediments. The collective assemblage of marine sandstone, shale, and carbonate begins to transgress across the subsiding continental shelf as a **drift sequence** of strata and marks the complete transition from rifting to drifting (Figure 9).

Fluvial sandstones and conglomerates grade upward into finer-grained and relatively thin marine shales and carbonates and mark the base of the Cambrian stratigraphic section in the southern Appalachians. Locally, relatively thin amygdaloidal basalt flows appear in an alternating sequence within the lowest parts of the coarse clastic strata. At some

Figure Atlantic SE.8 Sketch map of southeastern Laurentia during the Late Proterozoic and juvenile Iapetus Ocean.

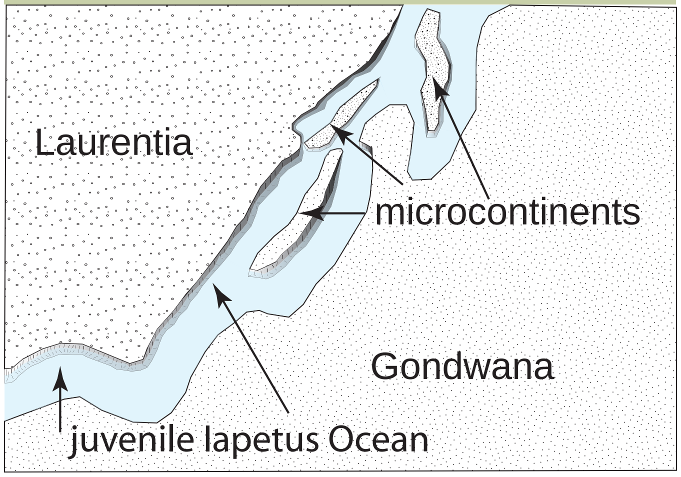
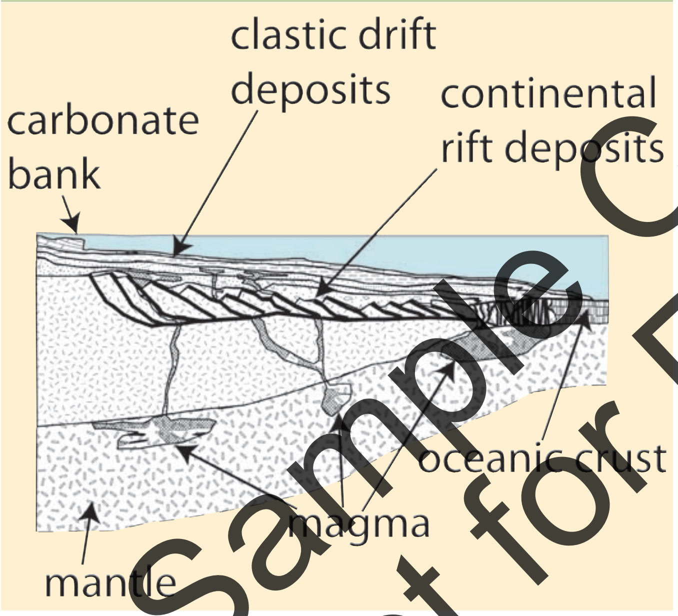


Figure Atlantic SE.9 Suggested profile of Laurentian passive margin during the latest Proterozoic and earliest Paleozoic.



localities in the Blue Ridge, no distinctive break occurs between the uppermost Proterozoic stratified sequence and the lowermost Cambrian conglomerates and sandstones. However, basal Cambrian strata overlie older rock units with a marked **unconformity** at many other localities. All of this reveals that the Cambrian strata compose the lower part of an onlapping, or transgressive, package of marine sedimentary rocks representing the drift sequence of the early **Iapetus** Ocean basin. An interesting aspect of the basal Cambrian conglomerates and sandstones is the relative abundance of large, somewhat angular clasts of fresh potassium feldspar. Weathering processes usually degrade feldspar minerals into clay on exposure to air and water, but the clasts in the onlapping Cambrian clastic sediments argue for very little weathering before deposition. Warm ambient temperatures and the presence of sufficient water favor a fast rate in the chemical decomposition of minerals during weathering. Although direct evidence supporting widespread glaciation during the Late Proterozoic in the Blue Ridge is lacking, essentially unweathered clastic feldspar grains in conglomerates of the lowermost Cambrian argues for rapid deposition under near-glacial temperatures. Basal Cambrian conglomerates from other localities in North America have similar characteristics and confirm that cold and dry climates existed across the continent at this time. No other significant rock fragments are present as clastic grains in the basal conglomerates and sandstones, a purity that suggests a stable source area of granitic composition with low relief. An extensively glaciated continent matches these criteria.

The basal sequence of fluvial and marine clastic strata grades upward into marine shales and thicker carbonate units. Dolomite and chert comprise the bulk of the carbonate rocks reflecting very shallow marine waters associated with a carbonate bank. Carbonate deposition dominated the passive margin of eastern Laurentia for all of the Cambrian and into the Ordovician. A slight **regression** occurred within the Late Cambrian as the Rome trough opened as a rift located to the west of the passive margin within a more interior area of Laurentia (Figure 10). Rifting uplifted the margins of the trough, which then shed clastic sediments eastward toward the passive margin. After the uplift and subsequent erosion, renewed carbonate deposition on the passive margin continued without interruption into the early Middle Ordovician (Figure 11).

Carbonate deposition on the passive margin during the Late Cambrian and Ordovician exhibits cyclic repetitions of deeper facies of limestone and dolomite grading upward into very shallow carbonates with algal mats. Ordovician carbonate sequences in this region consist predominantly of tidal-dominated, very thinly laminated dolomitic limestones.

Figure Atlantic SE.10 Sketch map of geography of Laurentian margin during the Cambrian.

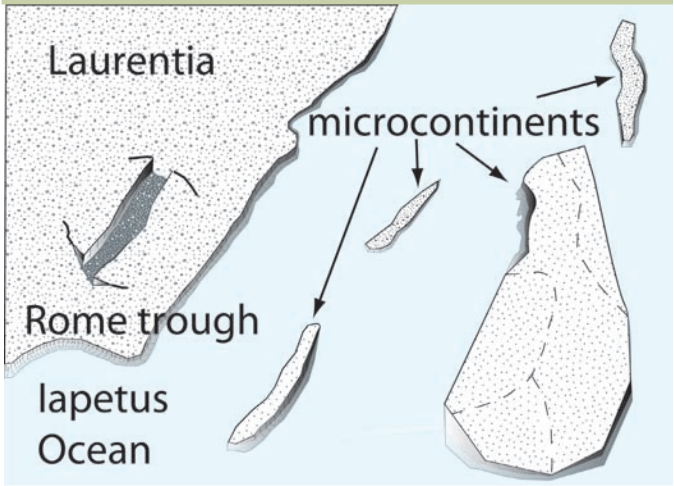
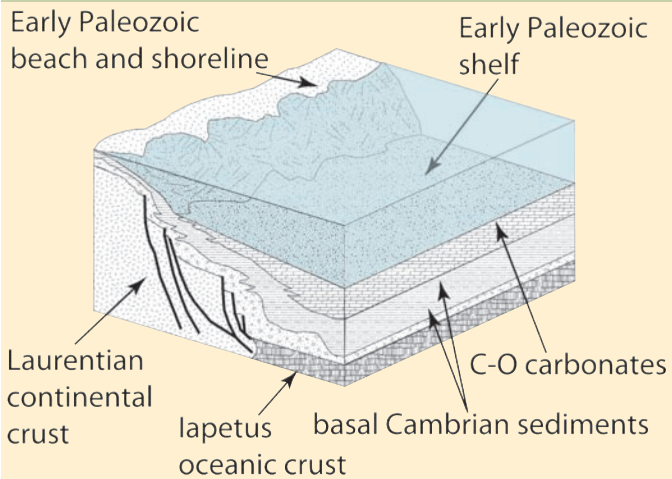


Figure Atlantic SE.11 Details of the Cambrian-Ordovician carbonate bank of eastern Laurentia.



Exposures of these very shallow carbonates above sea level enhanced the growth of solution-related karstic features along a horizon that later marked a prominent **disconformity**. The pits, closed depressions, collapse breccias, and sinkholes characterize a weathered surface within carbonate rocks that became favorable locations for economic mineral deposits including manganese, copper, lead, and zinc.

Evidence of continental slope and deeper sediments of Cambrian and Early Ordovician age, where preserved in areas that lay east of the carbonate bank, consists of thin and somewhat laterally discontinuous sandstone interfingering with mudrock and limestone. These strata generally reflect limited contributions of sediments from the continent shelf lying to the west. Our principle clues for reconstructing the paleogeographic setting of this time occur in deformed rocks that were transported great distances from their original position during the major tectonic events of younger Paleozoic age. Before establishing the remaining history of Paleozoic sedimentary rocks of eastern Laurentia, let us shift our focus to the Late Proterozoic and early Paleozoic geology of the Iapetus Ocean basin that bordered the passive margin.

Atlantic Southeast.5
Proterozoic and Early Paleozoic History of the Terranes Comprising the Piedmont

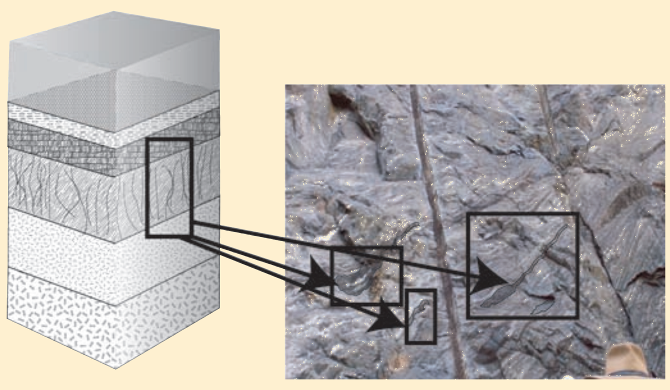
Most of our knowledge regarding the early geologic history of the Iapetus Ocean basin comes from careful studies and analyses of exotic and **suspect terranes** currently recognized within the Blue Ridge and Piedmont provinces. A **terrane** consists of an area of rocks possessing similar characteristics and structural histories. Usually, the size of a terrane is at least several tens of kilometers. However, later Paleozoic orogenic events in the Appalachians greatly reduced terrane dimensions by thinning and extending, stretching and pulling, compressing, folding, refolding, and shearing. Recognized terranes within the Appalachians possess continental or oceanic characteristics. Mixtures of relatively low-grade metasedimentary and metaigneous rocks characterize terranes that formed in the uppermost levels of the crust. Later tectonic events have not obliterated or greatly modified primary features of the rocks such as bedding and original stratigraphy. Rocks that formed at deeper levels in the terranes generally have higher degrees of metamorphism and exhibit multiple, overprinting phases of dominantly **ductile deformation** that obliterate all primary structures.

Terranes generally represent a variety of origins including fragments of continents, remnants of oceanic islands, intact or fragmented oceanic plateaus, and other possibilities. Paleomagnetic studies of rocks and/or fossils discovered within a terrane assist in determining its original geographic location, particularly if the terrane is relatively young and has not been overprinted by too many later events. An **exotic terrane** is one whose original location is reasonably known. The original geographic setting of a suspect terrane is not known with reasonable certainty. Recognized terranes in the Atlantic Southeast region ultimately originated with the Proterozoic rifting of Rodinia into smaller continents (in this case, Laurentia and Gondwana), continental fragments, and microcontinents. Many of the terranes recognized within the Blue Ridge are remnants of Laurentia that drifted far enough away from the mother continent to cultivate their own variation of a drift-related stratigraphic sequence. Isotopic analyses of other Blue Ridge terranes suggest that some could be fragments of Gondwana that either drifted closer to Laurentia over time or were simply left behind as their mother continent drifted farther away from Laurentia.

Fault zones (either brittle or ductile) delineate terrane boundaries. The incorporation of a terrane within an **orogen** is the result of either convergent or transform tectonics related to plate collision along active boundaries. Identification of a terrane boundary helps in unraveling the relative sequence of geologic and tectonic events leading to the collision. Terranes can experience tectonic activity before their involvement in a later collision. The process of one colliding terrane merging into another terrane or continent is called **docking**. The **suture zone** marks the docking event and includes the terrane boundary and **stitching plutons** that weld the masses together. Stitching plutons intrude rocks on both sides of a terrane boundary and have ages that are similar to the terrane boundaries.

Prominent fault zones, identification of ophiolite complexes, and recognition of stitching plutons provide evidence of terrane boundaries and suture zones in the Blue Ridge and Piedmont. Ophiolite complexes are segments of oceanic lithosphere and crust characterized by a distinctive association of rocks: basal ultramafic rocks overlain by

▶ **Figure Atlantic SE.12** Exposure of deformed and partially melted layers or blocks of amphibolite gneiss in a matrix of finer-grained feldspar-quartz rock. Note hat and tubular borings for blasting as references of scale. Several, but not all, of the amphibolites are highlighted. The amphibolites are interpreted as remnants of part of the ophiolite sequence as suggested by the linking arrows. U.S. 23-441 at Savannah Church, North Carolina.



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massive layers of gabbro, and an overlying complex of sheeted basaltic dikes, pillow lavas, and basaltic oceanic crust. Deep-sea muds and oozes comprise a thin sedimentary veneer capping the uppermost oceanic crust. Ophiolites in the Blue Ridge and Piedmont are recognized by their ultramafic and mafic compositions either as mappable contiguous bodies or as discontinuous, stretched, and thinned layers of centimeter-sized fragments within gneiss (Figure 12). Later deformation and metamorphism obliterated the originally continuous sequence from the ultramafic mantle through the oceanic crust comprising the ideal ophiolite. Nonetheless, the juxtaposition of ultramafic and mafic rocks even as discontinuous layers within gneiss faulted against Grenville basement gneisses or other bedrocks of continental origin delineates a terrane boundary. Paleozoic orogenic events overprinting earlier Paleozoic and late Proterozoic suture zones have made interpretations of the early Iapetus Ocean basin difficult, but not impossible.

Metamorphic rock types in the Piedmont Province range from slates to gneisses, greenstones to amphibolites, and quartzites to marbles. Protoliths include ophiolite complexes; mafic and felsic plutons associated with a **magmatic arc** or arcs; volcanic ash beds, tuffs, flows, and volcanic-related sedimentary rocks; quartz sandstones; mudrocks; and limestones and dolomites. Reported metamorphic grades range from lowest greenschist facies into upper amphibolite facies. Pressure types also vary from low- to high-pressure metamorphism. Compilations of mineral and whole-rock ages of Piedmont rocks date the origins of these rocks between the Late Proterozoic up through the Late Paleozoic. Shear zones and thrust faults dissect the Piedmont into smaller areas, each containing an internal coherent assemblage of characteristic rocks typical of exotic and suspect terranes.

The eastern segment of the Piedmont contains remnant magmatic arcs that formed during docking and collision events of terranes whose ages are older than the Iapetus Ocean. Plutonic rocks of the terranes fix the basement underlying these arcs as either oceanic or hybrid. Hybrid crust contains elements of both oceanic and continental settings and suggests a **subduction zone** origin involving a small continental fragment or microcontinent. Rodinia's dismemberment scattered small fragments of continental crust including microcontinents across Iapetus. Limited fossil data within terranes of the eastern Piedmont place their original position around the periphery of Iapetus in the vicinity of distal Gondwana, suggesting that Iapetus was a large ocean basin.

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Middle Ordovician through Late Paleozoic Geology and Tectonics

Taconic and Post-Taconic Paleozoic Geologic History of the Laurentian Continental Margin

Uplift and a regional regression during the Middle Ordovician resulted in extensive weathering and erosion of the Lower Paleozoic passive margin sequence of Laurentia. A regional **transgression** deposited a layer of younger carbonate sediments over weathered remnants of the earlier Paleozoic carbonate bank. Major subsidence adjacent to the shelf created a deep marine basin that began filling with submarine fan deposits including turbidite sequences and deep-water clastic sediments derived from eastern source areas. The drastic shift from the underlying passive margin sequence to this thick mass of mixed coarse- to fine-grained, immature clastic sediments including volcanic rock fragments reflects the tectonic origin for the strata deposited within a deep-sea, subduction-related trench. As the trench became completely filled, its sediments began drowning carbonate deposits with clastic material.

A wedge of Late Ordovician and Early Silurian clastic sediments overlies remnants of the subduction-related clastic sediments that overwhelmed the former Laurentian shelf margin during the Middle Ordovician (Figure 13). The very mature conglomerates, sands, and reddish muds reflect a mixture of beach, deltaic, and westward-flowing fluvial systems as part of a broad coastal plain along the flank of eroding highlands. The Lower Silurian red beds yield iron ore when the concentration of iron in certain thick layers is unusually high. Many beds of the Lower Silurian Clinton Group supplied ore for the iron and steel industry of the United States in the nineteenth and twentieth centuries. The Silurian clastic sequence graded westward into marine muds and carbonate sediments. Although erosion has removed part of the stratigraphic record of the later Silurian and Early Devonian in the Atlantic Southeast, deposition continued uninterrupted through part of the Early Devonian. Depositional environments of the

▶ **Figure Atlantic SE.13** Folded and thrust-faulted Upper Ordovician and Lower Silurian clastic sediments in southwestern Virginia. Red coloration of sandstones on the left results from iron oxides. Deformation of the strata resulted from Alleghanian Orogeny in Late Paleozoic.

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Devonian ranged from deep basin with accumulations of reduced organic-rich mud (deprived of oxygen) upward into shallower waters containing coarser-grained sandy and carbonate sediments. Devonian black shales of the deeper marine facies serve as source beds for petroleum and natural gas that later migrated and accumulated within overlying reservoir rocks, many of which are still in production. Carbonate rocks of the Lower Devonian yield a prolific quantity of diverse marine fossils. The unusually pure layers of Devonian marine sandstones provide excellent sources of sand for making high-quality glass and glassware. Within the lower interval of the black shale, layers of altered volcanic ash, derived from an eastern source, are locally capped by an interval of chert. Rapid filling of the Appalachian basin began during the middle Devonian. Fluvial and deltaic sediments associated with a westward-advancing fluvial system encroached into the region as the Catskill Delta sequence. Catskill strata occur in more northerly parts of the Appalachian Basin, but intervals of brown and red shale with greenish gray sandstone and black shale are their distant equivalents present in the southern parts of the Appalachian Basin. Lower Mississippian fluvial sediments overlie the Devonian and grade upward into a marine mud and carbonate sequence.

Cyclic deposits characterize Lower Pennsylvanian strata, beginning with a basal sequence of nonmarine fluvial sandstones and associated floodplain deposits. The fluvial systems flowed through a broad area containing lakes and swamps. Relative submergence of this large coastal plain resulted in the progressive deposition of marine shale and limestone. Relative sea level began to lower as reflected by deposition of brackish marine shale over the limestone. Continued regression leads to the start of the cycle again with fluvial channels cutting into the upper parts of the brackish marine shale. Within the Appalachians, most of these cyclic deposits appear within the Appalachian Plateaus, but small areas of the section of the Pennsylvanian locally occur in the western Valley and Ridge. Organic sediments of the swamp deposits eventually became peat, which transformed into the abundant bituminous coal deposits of the Appalachians. Literally hundreds of cycles can be counted throughout the region, demonstrating the tremendous volume of the economic coal resources present. Above the coal-bearing intervals, a sequence of fluvial and floodplain deposits of conglomerate, sandstone, and reddish-colored mudrocks persist through the remainder of the exposed section of Pennsylvanian strata. This uppermost part of the section comprises a westward-advancing clastic wedge deposited in front of a highland region.

Bituminous coal is one of the progressive rankings of coal based on the amount of carbon present. Lignite is the category for low-rank coals, bituminous for middle ranks, and anthracite has the highest amount of carbon present within the coal. Lower amounts of carbon within the coal permit greater amounts of noncarbon materials to be present including sulfide minerals such as pyrite. Waste rock excavated during mining of bituminous coal exposes large amounts of disseminated pyrite to weathering. Iron sulfide decomposes into various iron and sulfur compounds including sulfuric acid, which enters streams draining the mined area. Acid waters have significant and deleterious environmental effects within local watersheds. Laws and regulations for reclaiming old and recently depleted mines attempt to minimize the environmental damage from acid waters through requirements that isolate and seal the pyrite-bearing material from further exposure to the atmosphere and surface waters.

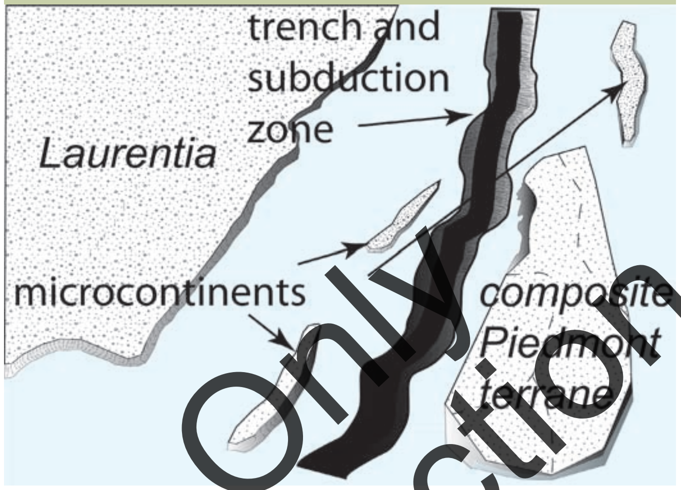
Major industrial centers originally located in the central and southern Appalachians because of the close proximity to bituminous coal resources. In particular, the close proximity of coal, limestone, iron ore, and major rivers for transportation were major factors in the success of the early iron and steel industry in the central and southern Appalachians. Coal was fused and partially burned to make coke, which burned at higher temperatures in a blast furnace. Limestone acted as a flux when mixed with iron ore in the furnace to smelt the raw iron, or pig iron, from the ore. The molten flux floated on top of the liquid iron to form porous, volcanic-looking material called slag. Piles of slag could be seen as tall hills in many of the old steel mills that populated this part of the Appalachian Mountains.

Paleozoic Geology and Tectonic History of the Piedmont

Subduction zones mark the descent of one plate under another during their collision along a **convergent plate boundary**. Horizontally directed compressive forces and stresses generate a consistent sequence of topographic characteristics at subduction zones including a trench, **accretionary complex**, **forearc** basin, and a magmatic or volcanic arc. As opposed to the extensional rifting and normal faulting of divergent plate boundaries, compressive folding and reverse faulting deform rocks caught within the vise of convergent boundaries. Rifting at divergent boundaries expresses the upward rise of a convecting plume or mass of asthenosphere and culminates with lateral drifting of continents as the new lithosphere and crust cool. Subduction zones form because the convective motion begins a downward path into the mantle. The downward turn effectively drags the overlying oceanic crust, creating a deep trench in the sea floor. The deepest known trenches reach depths as much as 35,000 feet. As subduction proceeds, the trench deepens. Any sediment or weakly consolidated material on the sea floor is scraped off by the overlying plate, accumulating into a wedge-shaped mass of squeezed and thrusted sediments and rocks known as an accretionary complex. The complex grows progressively wider and taller as subduction continues, eventually reaching the trench. The subducted lithosphere reached depths within the mantle where water and other volatiles can escape from the descending rocks into the overlying mantle leading to the generation of magmas and volcanoes of the volcanic arc. Instability of the growing accretionary complex leads to its partial collapse, opening a basin on top of the accretionary complex and in front of the volcanic arc (the forearc basin). Submarine fans and turbidite flows emanating from the elevated volcanic arc soon begin to accumulate in the basin as their escape toward the trench is now slowed. Parts of the descending oceanic crust may be pried off during subduction below the accretionary wedge and become incorporated into its base. Compression within the wedge results in folding, and thrust faulting. Thrust faults climb upward from the base of the accretionary complex and outward toward the trench and may eventually affect parts of the overlying forearc basin. A chaotic mixture (mélange) forms and consists of clastic sediment, deep-sea oozes and muds, immature sands, breccias, conglomerates, volcanic rock fragments, and even pieces of the ocean floor and crust (ophiolite material).

Scraping of the descending slab may shear off a large flake or fragment of oceanic lithosphere that becomes embedded within the deforming accretionary complex as either a partial (dismembered) or intact ophiolite. The dimensions of a subduction zone are capable of incorporating ophiolites or large slabs of other intact rock masses that have areas reaching several hundreds of meters.

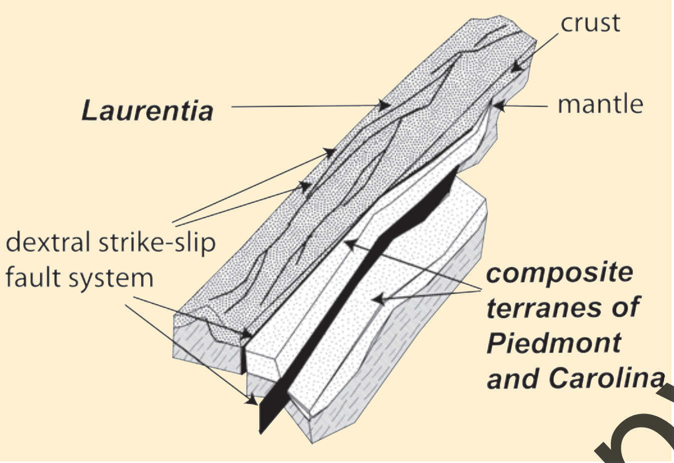
Figure Atlantic SE.14 Sketch map of western Iapetus and the eastern Laurentian margin during the middle Ordovician. A subduction zone and trench formed in front of the advancing composite terrane of the Piedmont. Eventually, the eastern margin of Laurentia partially descended in this trench resulting in the Taconic Orogeny.



Subduction around Iapetus began during the Cambrian as marked by docking of older terranes containing Late Proterozoic sedimentary rocks docking with other small terranes into larger masses (a **composite terrane**). An eastward-dipping subduction zone formed in front of approaching terranes of the eastern Blue Ridge and western Piedmont, partially dragging the eastern margin of Laurentia downward, an event that triggered the Ordovician **Taconic Orogeny** (Figure 14). The oblique approach of this progressive collision resulted in terranes of the western Piedmont and eastern Blue Ridge docking to Laurentia before the arrival of the eastern Piedmont terranes. Late Ordovician plutons stitched a suture whose trace lies somewhere at depth and within a major though-going shear, the Central Piedmont Shear Zone. Uplift of terranes above the subduction zone and/or back-thrusting them toward Laurentia accounts for uplift, erosion, and subsidence of the remaining passive margin during the Late Ordovician before its flooding with clastic sediments during the Early Silurian.

Iapetus continued to close after the events of the Taconic Orogeny. Post-Taconic granitic plutons intruded through shear zones that juxtaposed shallow and deep segments of metamorphosed terranes. During the Devonian, the closure of Iapetus changed from a mode dominated by subduction to one characterized by right-handed (dextral) strike-slip motion combined with compression, a type of motion known as **transpression** (Figure 15). The Brevard Zone, one of several major shear zones reactivated at this time, parallels the regional strike of the Blue Ridge and generally lies at the base of the Blue Ridge Front in western North Carolina. Many of the Taconic thrust faults associated with subduction zones became reactivated as Devonian dextral shear zones. The timing and size of these oblique, regional shear zones reflects an origin rooted with a large-scale docking event, possibly a large microcontinent, with Laurentia.

Figure Atlantic SE.15 Diagram demonstrating dextral strike-slip tectonics of the Acadian Orogeny. Oblique convergence of the buoyant composite terranes of Piedmont and Carolina with Laurentia resulted in dextral shearing. The collision reactivated older Taconic faults, which also experienced dextral shearing. Note that the closest part of the Piedmont terrane was involved with shearing long before more distant parts on the trailing edge of the terrane. Although absolute ages of deformed rocks in both parts of the larger terrane can indicate a significant discrepancy in times of shearing, the nature of oblique collisions correctly reveals that the two ages are end points of a progressive series and not two separate events.

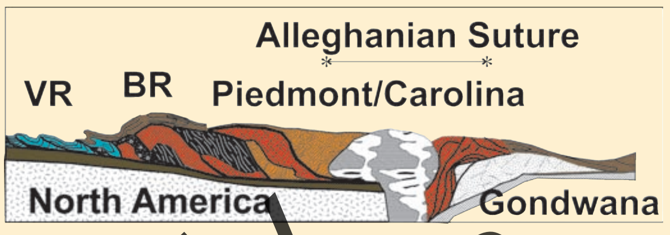


The San Andreas Fault Zone, a classic **strike-slip fault**, experienced a similar history of transition from a subduction to a transpressive mode of collision. Collectively, the dextral shearing, granitic magmas, and accompanying low-grade metamorphic processes comprise the **Acadian** Orogeny in the Southern Appalachians.

Devonian magmas in the Piedmont and Blue Ridge are mostly granitic but are associated with significant economic mineral deposits. Over an approximate area of 500 km^2, the Spruce Pine district in the Blue Ridge of North Carolina contains several thousand pegmatite bodies and very light-colored granitoid intrusions known as alaskites. Economic deposits of minerals present within the Spruce Pine district include kyanite, chromite, beryl, potassium feldspar, muscovite, kaolin, and quartz (of extremely high quality for fiber optics, optical glass, and microchips for electronics). Gemstones produced include emeralds, aquamarine, and golden beryl. Uranium minerals are also present in the pegmatite bodies. Within the Piedmont, the Acadian granites are larger in area, display more effects of metamorphism, and have created significant mineralization in contact with host schistose and metavolcanic rocks including the famous spodumene deposits within the Kings Mountain district.

The final events in the closure of Iapetus occurred during the Late Paleozoic **Alleghanian** Orogeny (Figure 16). Metamorphism and deformation of this event was strong enough to overprint many effects of the Taconic and Acadian events through reactivation as structures in the Alleghanian sequence of compression. The compression resulted in large-scale lateral overthrusting of the Valley and Ridge, Blue Ridge, and Piedmont along detachment horizons beginning

Figure Atlantic SE.16 Schematic profile of the Alleghanian Orogeny. Gondwana collided with Laurentia and thrust the rocks and structures formed during the Acadian and Taconic events westward along a detachment zone, which can be traced below the Appalachian orogen eastward below the present Coastal Plain. VR represents the Valley and Ridge. BR is the Blue Ridge.

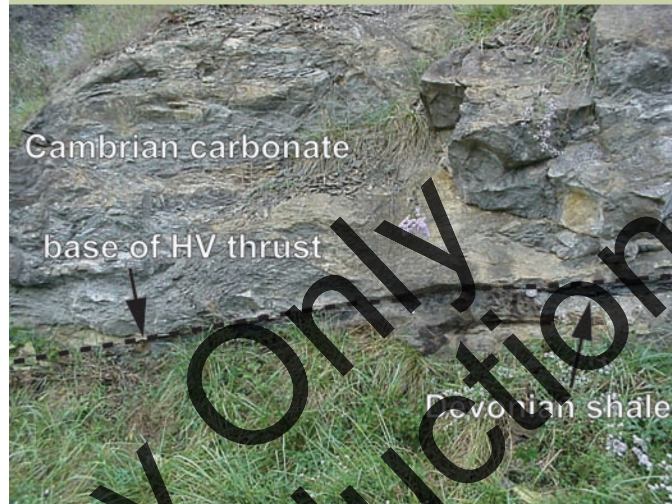


near the base of the passive margin sequence. Compression also reactivated Acadian shear zones as thrust faults. Widespread granitic plutons in the Piedmont comprise the largest orogenic-related magmas in the Atlantic Southeast and are prized as sources of building and dimension stone for many cities and monuments across the United States. Alleghanian regional metamorphism reached upper amphibolite facies, which is lower than the peak Taconic metamorphic zones in the Blue Ridge. However, Alleghanian metamorphic recrystallization was pervasive and obliterated characteristic features of both the Taconic and Acadian orogenic events. Metamorphism accompanied granite magmatism, but many of the Alleghanian plutons such as the Rolesville **batholith** near Raleigh, North Carolina outlasted the peak metamorphism. Some Alleghanian thrust faults are clearly pre-Alleghanian metamorphism, others are contemporaneous with the regional recrystallization, while others moved well after metamorphism. Sometime during the Early Pennsylvanian within the Piedmont, Alleghanian thrusting transformed into Alleghanian dextral shear zones, some of which may record strike separations of up to 200 km.

Detachment horizons or faults occur when a relatively incompetent or weak layer within a horizontally layered pile of sedimentary rocks is squeezed and pushed from the side. Strata overlying the weaker layer move as a unit in the direction of the applied stress while the strata below remain relatively stationary. The detachment surface progressively moves through the weak layer until a lens or interbedded layer of stronger rock forces the detachment to climb upward at a steeper angle. Eventually, the detachment surface enters into an overlying weaker layer where that passage follows a nearly horizontal direction once again. The Paleozoic stratigraphy of the Appalachians favored using weaker shale intervals for subhorizontal motion along detachments (Figure 17), whereas sandstones act as more competent units with higher angled thrust faults. In a similar, but not identical, manner, horizontal detachments formed in crystalline rocks of the Piedmont and Blue Ridge. Movement along the detachments created long, linear trains of subparallel plunging anticlines and synclines in the Paleozoic sedimentary rocks now existing as the Valley and Ridge. Stacks of crystalline thrust sheets formed in both the Piedmont and Blue Ridge as a consequence of Alleghanian compression. Thrusting began during the early Carboniferous within Piedmont crystalline thrust sheets and became progressively younger toward the west with the emplacement of the youngest thrust sheets in the Valley and Ridge in the Permian. The main event triggering the Alleghanian Orogeny was the oblique collision of Laurentia with a comparable-sized Gondwanan continent such as Africa. Interestingly, the change from thrusting to dextral strike-slip motions in the Piedmont resulted in Early Pennsylvanian uplift and erosion of marginal strata in the Valley and Ridge. Continued transpression in the Piedmont created push-up ridges that quickly eroded releasing pulses of coarse-grained clastic wedges across the wide coastal plain in front of the uplifted hinterland.

The Alleghanian Orogeny is part of a global system of colliding continents that welded together during the Late Paleozoic as the supercontinent Pangaea. The Atlantic Southeast region is fortunate to have rocks that recorded the time and history of events that transpired between the formation of the most recent supercontinents, Rodinia and Pangaea. Just as its predecessor broke apart into smaller continental masses that drifted away, Pangaea began to rift and separate into separate continents that we now recognize as North America, South America, Africa, and Europe. We pick up their geologic histories as we progress forward in time into the Mesozoic and Cenozoic.

▶ Figure Atlantic SE.17 Hunter Valley thrust near Duffield, Virginia. Cambrian carbonate (Conasauga Group, Middle Cambrian) of hanging wall section in contact with Devonian shale. Brunton pocket transit along the trace of fault toward the right of the photograph. The Devonian shale is ductile along the fault, whereas the overlying carbonate deformed in a more brittle manner. HV stands for the Hunter Valley thrust fault.



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Atlantic Southeast.7 Mesozoic and Cenozoic Geology and Tectonics

Early Mesozoic Rift Basins

Pangaea began rifting during latest Paleozoic time in the southern Appalachians. Linear trends of brittle fractures, discordant zones of silicified fault breccia, and thick veins of milky quartz crosscut older Alleghanian features of Piedmont rocks at low, oblique angles. In Virginia and North Carolina, Late Triassic rift basins unconformably overlie Piedmont rocks, including these zones of brittle fractures. The relative age and regional trends of the brittle fracture zones suggest that tensile forces and stress fields responsible for their formation progressively initiated continental uplift and extension necessary for the younger rift basins.

Steeply dipping normal fault systems border the Late Triassic rift basins. In some basins, the main border fault dips toward the northwest, whereas in others, the dip is toward the southeast. Active faulting occurred during deposition of sediments within the basins. Strata dip toward the southeast in basins bordered by a northwest-dipping border fault. The opposite is true for basins bordered by southeast-dipping faults. Deep drilling records and geophysical studies reveal the presence of additional early Mesozoic rift basins deeply buried below the Coastal Plain and the present continental shelf. Thick sequences of younger strata overlie these buried basins. Somewhat later in the Triassic and early Jurassic, dikes and sills of diabase and flows of basalt intruded and flowed above the sediments filling the basins, as well as the surrounding rocks of the Piedmont (Figure 18). The parent magmas for these mafic igneous rocks ultimately created the embryonic crust underlying the North Atlantic Ocean. The history of the early Mesozoic rift basins is similar to those associated with the Late Proterozoic breakup of Rodinia.

The stratigraphy of the basins follows a characteristic and predictable threefold sequence: (1) a basal conglomerate, containing clasts of both granitic rocks and gneiss, and

▶ Figure Atlantic SE.18 Jurassic dike exhibiting spheroidal weathering in the Piedmont of North Carolina.

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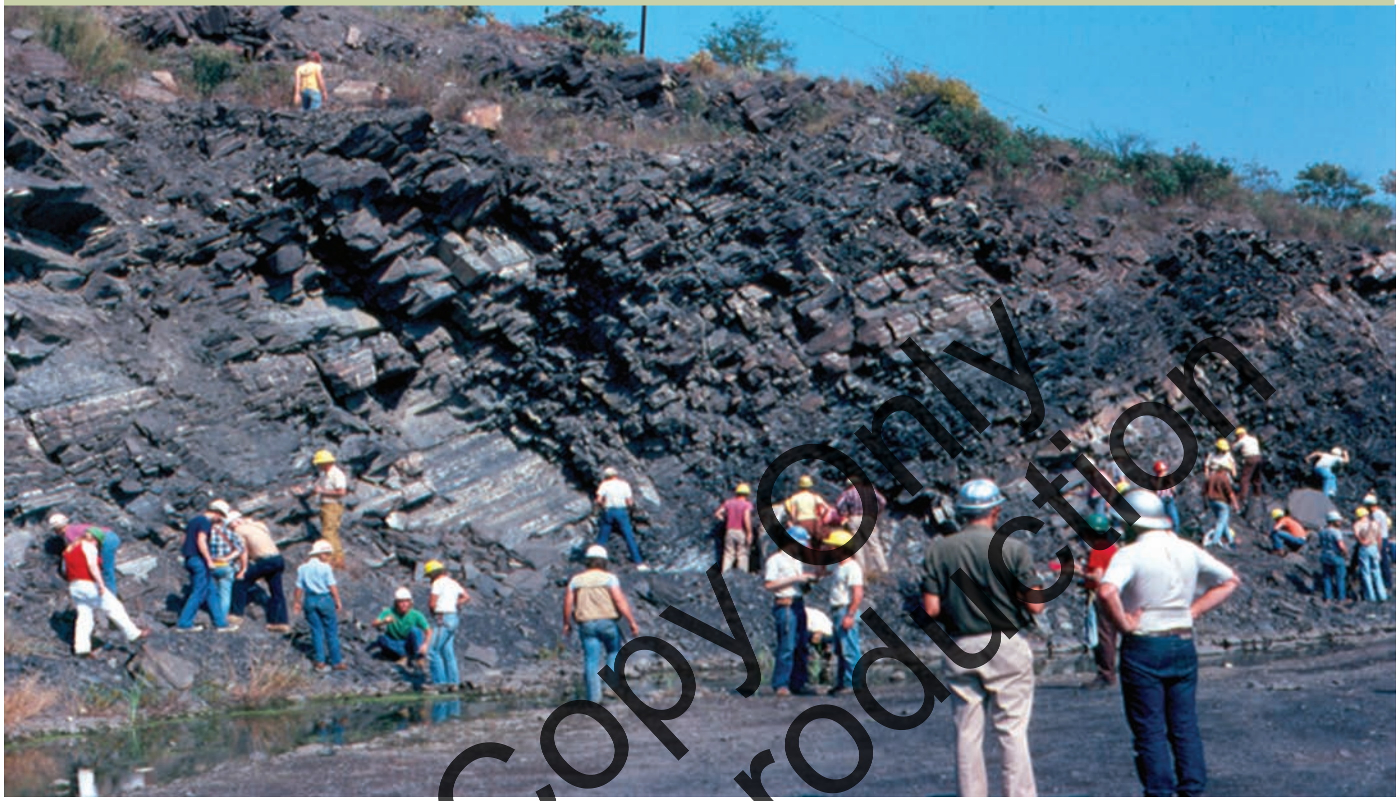
Figure Atlantic SE.19 Inclined strata of Cow Branch Formation in a quarry near Eden, North Carolina. This locality is within the Dan River Basin, a Mesozoic rift basin.



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coarse-grained arkosic sandstone; (2) an overlying sequence of interbedded dark gray to black fossiliferous siltstone (Figure 19), organic-rich shale, and thin coal layers; (3) and reddish brown siltstone and mudstone, arkosic to pebbly sandstone, and conglomerate. The strata reflect fluvial and lake environments within the interior of the basins bordered by a combination of fluvial/alluvial fan environments adjacent to the border faults. Deep drilling in buried basins under the present continental shelf reveals thick sequences of evaporite minerals and carbonate rocks as additional characteristic depositional facies. Fossils document a diverse record of life including plants (pollen, spores, leafs, twigs, roots, and wood), invertebrates, and vertebrates (fish and tetrapods including tracks and footprints) (Figure 20).

Figure Atlantic SE.20 Vertebrate footprint preserved in Cow Branch Formation, Dan River Basin, Eden, North Carolina.

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Rift-to-Drift Transition

Mesozoic and younger strata exposed along the continental margins of eastern North America, North Africa, and Western Europe document the progressive changes whereby continental rift facies become drift facies of a passive margin sequence. A seaward-thickening wedge of both nonmarine and marine strata comprises the exposed Mesozoic drift sequence in the Coastal Plain. A prominent unconformity separates Early Cretaceous basal strata of the Coastal Plain sequence from rocks of the underlying Piedmont including the Late Triassic rift basins and younger basalts. Significant weathering and erosion of the Piedmont during an interval spanning tens of millions of years established a land surface of relatively low relief. However, a thick series of Jurassic carbonates and evaporite deposits overlie the buried rift basins. An interval of coarse-grained clastic sedimentary rocks of Cretaceous age overlies the carbonate sequence and is similar to thinner strata exposed in the Coastal Plain. The steady lateral migration of this clastic wedge eventually transgressed over the continental margin. By Late Cretaceous time, the transgression had reached the Fall Line, which delineates the western edge of the exposed Coastal Plain.

The Fall Line refers to a remarkably consistent trend of a narrow zone of small waterfalls common to all streams flowing from the Piedmont into the Coastal Plain. This "line of falls" significantly impeded exploration and settlement to early colonists dependent on rivers and streams for major transportation. The Fall Line results from the higher elevations left by resistant weathering of quartz-rich crystalline rocks of the Piedmont relative to lower elevations of the less resistant semiconsolidated strata of the Coastal Plain. During the erosion of the Piedmont before the Late Cretaceous, a significant topographic break existed at the Fall Line that effectively stopped the westward marine transgression of the Cretaceous clastic wedge across an eroded continental shelf inclined gently to the east. This imparted a very low angle of primary dip away from Piedmont toward the outer Coastal Plain and continental shelf in successive Coastal Plain strata.

Lower Cretaceous units of the exposed Coastal Plain section consist of a succession of fluvial and deltaic strata that laterally grade eastward into coarse-grained clastic sediments deposited in open marine shelf, lagoonal, and carbonate bank/reef environments. A thick sequence of coarse-grained conglomerates and arkosic sandstones grades upward from the base of the Lower Cretaceous units into clay beds and finer-grained sandstones. At some localities south of North Carolina, the clay layers become thick and consist of very pure economic deposits of kaolin. Sedimentary structures such as desiccation features, slump structures, and cross bedding, and remnants of woody plant material and root casts attest to the fluvial origin of the exposed Lower Cretaceous strata. Decreased grain sizes and better maturity of overlying sand, mud, and marl marks the completion of the rift-to-drift transition Lower Cretaceous.

The Late Cretaceous time interval reflects complex shifting of deltas, prodeltas, delta plains, and marine shelf facies across the continental shelf and margin. Upper Cretaceous thin sands, dark clays, cross-bedded micaceous sands, and gravels represent deposits within either a lower delta plain or a delta front environment. Burrows and channels disrupt bedding. Fragments of petrified wood coated with pyrite occur in other strata that also contain rounded clasts of pure kaolin and thicker beds of pure clay. Some layers consist of a mixture of glauconite mixed with clay, and thin layers of quartz sand containing phosphate pebbles and abraded fragments of bone and shells. The clastic layers change facies laterally into abundantly fossiliferous marine limestone beds containing gigantic fossil oysters. Some of the Upper Cretaceous units present in the coastal plain of North Carolina are either absent in northern South Carolina or present only as very thin beds. This distribution resulted from the presence of the emerging Cape Fear Arch. This structure greatly influenced the patterns of deposition and the distribution of sedimentary facies. Thinner sections of Upper Cretaceous strata coincide with the crest of the arch, whereas thicker and more complete sections occur as deeper embayed basins along its flanks. The gentle dips of strata away from the crest of the crest suggest the arch originated as a rising fold, possibly a domelike feature related to regional warping of the continental shelf at this time.

Tertiary and Quaternary Geology

Cenozoic strata preserve a record of repeated intervals of shallow marine transgressions and regressions of marine waters in the Coastal Plain. Cyclic changes in climate during an overall cooling from the much warmer global temperatures in the Cretaceous provided the greatest factors driving these changes in global, or eustatic, sea level. Local variations in patterns of sedimentary facies reflect additional tectonic influences on deposition. Cenozoic strata generally become younger and lower in elevation outward from the inner Coastal Plain toward the present-day shoreline and outlying continental shelf.

Recall that a relative rise in sea level results in a transgression, whereas a relative drop in sea level results in a regression. Transgressions, then, generally deposit new sediment, whereas regressions erode existing sediments and older strata exposed by the falling sea. Sea level constitutes the regional base level for streams, which, by definition, is the elevation below which no fluvial erosion occurs. Streams maintain a dynamic balance among erosion, transportation, and deposition of their sediment load. Significant lowering of base level drives the stream to actively erode down through its channel. Strong and rapid downward erosion creates entrenched stream meanders. Cenozoic regressions eroded older Coastal Plain strata leaving partial remnants in entrenched stream channels and tributaries. Thick aprons of coarse-grained, nonmarine sediments are typical deposits of a regression. Thinner and finer-grained marine strata result from a transgression. Subsequent rises in sea level (base level) deposit finer-grained and texturally mature sediments above eroded and dissected surfaces that contain remnants of coarser-grained and less mature regressive deposits. Transgressions initially enter and fill entrenched stream channels before eventually merging as laterally extensive sheets or layers of sediments as sea level rises progressively. A basic understanding of transgression and regression effects on deposition is necessary for understanding all of the subtle changes in Coastal Plain deposits during the Cenozoic.

The oldest Cenozoic strata are Paleocene in age and consist of sands, clays, and muds deposited in open marine waters of the continental shelf, or shallower and more restricted environments associated with barrier islands and the back-barrier lagoons, beaches and estuaries, and river environments. A significant transgression during the Eocene deposited lime-rich mud rocks and fossiliferous limestones on a broad but shallow continental shelf bordered by a narrow coastal plain. Fossils within the carbonate strata provide excellent correlations with similar transgressive cycles in other parts of the world. Miocene marine limestones unconformably overlie Eocene strata in the exposed Coastal Plain, but seismic studies on the outer continental margin demonstrate a more complete Miocene transgression occurred with a lower sequence of clastic strata underlying the limestones. The landward limit of the Miocene transgression lay west of the exposed Miocene strata in the Coastal Plain. Local remnants of a marine limestone unit, possibly of Miocene age, directly overlie Piedmont crystalline rocks west of the Fall Line in central North Carolina.

Pliocene and younger transgressions in the Cenozoic were not as extensive as those of the Eocene and Miocene. Older Pliocene deposits are regressive and generally consist of sands and gravels containing pebbles of phosphate, carbonized branches and twigs of plants, rip-up clasts of older sediments, and calcareous sands. Finer-grained, fossiliferous quartz sands, and sandy and clay-rich muds embody younger Pliocene transgressive deposits. Fossils in the sands contain a rich assemblage of clams and snails, very large oysters, and teeth and bones of vertebrate fossils. Lower Pleistocene deposits contain very fossiliferous marine sands and muds sometimes exposed as a hard, cemented coquina ("beachrock") at isolated locations along the coastline. Younger Quaternary deposits include beach and barrier island sands and dune deposits, and lagoonal silts and muds mixed with fluvial sands. Further inland from the coastal counties, gravels, clay-rich silts, and sands of fluvial origin mixed with dune deposits, alluvium, and colluvial material of probable Pliocene and Pleistocene ages unconformably overlie highly weathered older Coastal Plain strata and Piedmont rocks. Some of the sand deposits are valued for their purity as high-silica resources (Figure 21). Recent erosion has isolated these inland or upland deposits from their equivalent marine deposits present in the outer coastal plain.

Active sedimentation in the present-day coastal zone is part of a regional transgression induced by melting of Pleistocene glaciers over the past 10,000 to 20,000 years. The chain of barrier islands that lie seaward of bays and estuaries along the coast offer insights to the processes assisting the landward migration of the barrier islands. Littoral currents formed by breaking waves along the beach establish a seasonal direction of sand movement parallel to the length of the islands. Overwash of sand from the seaward face of the islands into small lobate deltas document the role of wave action in storms pushing sediment across the islands. Aeolian dunes (Figure 22) overlapping older marsh, back-barrier, and estuarine deposits on the lee side of the islands signify the important role of steady breezes in moving the sand. Tidal inlets form as breaks in the line of islands that permit the movement of daily tidal currents to move sediment. As inlets migrate or shift over time, so do the tidal channels and deltas, and overall expansion and contraction of the islands results. The time scale for these dynamic changes is measured in years and tens of years, resulting in constant threats to human structures willfully placed within this dynamic zone. Regional problems and

▶ **Figure Atlantic SE.21** Pliocene Citronelle Formation ("Lilesville Gravels") near Lilesville, North Carolina. Weathering of very minor iron oxide minerals has stained the surface of this unit into its distinctive red, yellow, and orange colors. Note the channels filled with the gravels cut into older weathered strata below.

John R. Huntsman

Figure Atlantic SE.22 Dune deposits exposed by action of tropical storm, southern New Hanover County, North Carolina. Note cross bedding at top of eroded bluff.

John R. Huntsman

expenses created by coastal dynamics and geologic processes provide plenty of fuel for controversy in the fields of science, engineering, urban and cultural development, politics, and economics.

The Cenozoic Era contains a repeated history of climatic changes accompanied by rising and falling sea levels. Pleistocene glaciers advanced over North America at least four times. Each advance is associated with a major regression, and each interval of warmer climates between the glacial advances contains a period of transgression. Global records indicate that the Cenozoic records a gradual global cooling from a Cretaceous maximum temperature, which far exceeded the average global temperature of today. The subject of global warming constitutes the center of discussions in many environmental, economic, and political circles. The current debates question the role of human activity in the form of releasing greenhouse gases into the atmosphere as major factors in global warming despite the obvious geologic observations that present-day Earth is not nearly as warm as it was during previous times of global warming. It is entirely possible that even given the probable increase in the rate of global warming from automobile and industrial emissions of greenhouse gases, the peak of global temperatures may not be as catastrophic as some contend. However, the documented dynamic changes within the coastal zone over the past hundred years suggest that even limited increases in sea levels produce significant problems for humans. To error greatly on the side of caution in releasing additional gases that can contribute to more rapid rates of global warming is a viable and perhaps practical choice. We have a moral and ethical responsibility to leave a habitat for successive generations to experience the wonderful aspects of geology.

Carolina Bays are interesting phenomena of geology present widely within the Coastal Plain of the Atlantic Southeast region, but a majority of geologists and earth scientists has yet to completely agree on their origin or origins. More than 500,000 Carolina Bays occur as circular to elliptical depressions from Delaware and New Jersey to Florida, but they are particularly concentrated in eastern regions of the Carolinas. Some of the bays are occupied by lakes, whereas others may be wetlands populated by Bay trees, which is the root of the term *Carolina Bay*. Most of the bays are elliptical in plan with an elongation direction trending NNW-SSE. The bays have variable lengths and widths from a few meters to several hundreds of meters. Small ridges of sand generally occur on the southeastern margins of the bays. At some locales, the sand ridges merge outward into fields and arrays of curved and linear dunes (parabolic and longitudinal). Carolina Bays formed between 100,000 and 200,000 years ago based on the age of underlying strata or unconsolidated surface deposits. Various hypotheses exist to explain the bays, including natural geologic processes and catastrophic encounters with extraterrestrial objects. A suggested model for the origin of Carolina Bays focuses on prevailing northwest winds blowing southeast during arid to semiarid conditions of a Pleistocene glacial episode. Water subsequently accumulated in deflation basins leading to wind- and wave-driven sand deposits along the southeastern margins of the depressions. Because Carolina Bays are unique geologic features, their exact origin will continue to be controversial and unsettled.

Chesapeake Bay Impact

A comet or an asteroid with a diameter of 3 to 5 km burst into the shallow submerged continental shelf in the area of southern Chesapeake Bay about 35 million years ago. The impact created an enormous crater measuring 85 km in diameter and more than 1 km in depth that is now buried under about 500 m of Cenozoic strata. Rock fragments ripped from strata underlying the continental shelf, including the deeper rocks of the basement, blew upward during the impact, and then resettled into the crater as a chaotic mass of slump blocks and brecciated rubble. The cataclysmic event created a low area on the continental shelf that has affected younger geologic processes including diversion of streams and watersheds, subsidence of land areas over the crater, faulting, and interference with groundwater systems. Some of these effects still pose concerns for today's population in the southeastern Virginia and the eastern shore of Maryland. Apart from localized effects in the area created during the impact, significant disruptions to contemporaneous geologic processes throughout the Atlantic Southeast are not yet recognized and confirmed.

Atlantic Southeast.8 Natural and Anthropogenic Hazards of the Atlantic Southeast Region

Recent Seismic Activity and Cenozoic Tectonics

The history of seismic events throughout the southeastern region indicates that seismic activity is not randomly distributed but occurs as episodic events within clustered areas. Seismologists and geologists recognize this pattern as the result of earthquakes generated within the North American plate and not as the product of interactions at a convergent or **transform plate boundary**. Intraplate earthquakes result when dominantly compressive, NNE-trending horizontal stresses currently existing in this part of the North American plate interact with local structures such as buried border faults of Mesozoic basins or reactivated shear zones and terrane boundaries in older basement rocks. Such interactions are unlikely to produce frequent, high-magnitude earthquakes in this region.

The Charleston earthquake discussed in the introduction had an estimated magnitude of greater than 7.0 and documented intensity of X. Widespread damage to structures occurred within an epicentral region of approximately 30 × 50 km. Felt reports of the earthquake came from areas as far away as central Ohio and western West Virginia. No fault scarp of the earthquake is known as a result of the unconsolidated nature of the Coastal Plain sediments throughout the affected area. Geomorphologic and other indirect studies suggest that the epicenter of the earthquake overlays the junction of two faults: a high-angle, northwesterly-trending fault and the southern segment of a regionally extensive, northeast-trending fault zone. Analyses of stream terraces show narrow zones of anomalous channel characteristics that defy explanation by normal processes of erosion and deposition. The epicentral area of the earthquake abounded with examples of liquefaction related to seismic shaking. Liquefaction requires saturated conditions in unconsolidated sediments to form clastic dikes, sand blows, and lateral spreading of the ground triggered by seismic shaking. In the Charleston area, evidence of seismic-induced liquefaction occurs in sediments that are buried to maximum depths of less than several meters and the age of which is younger than 250,000 years. Recent discoveries of several prehistoric liquefaction events observed in the walls of excavated trenches suggest a recurrence interval of approximately 1,000 years for damaging earthquakes (magnitude > 5.5) in the Charleston area.

Seismic hazard maps indicate that the Charleston area has the potential for significant ground acceleration (in excess of 10% g, or 1 m/sec/sec) at least once within the next 50 years. Similar peak values are projected for the central area of the eastern Tennessee seismic region that extends and overlaps with northeastern Alabama, northwestern Georgia, western North Carolina, southwestern Virginia, and southeastern West Virginia. The Giles County area, situated along the border of Virginia and West Virginia, is another area of recent moderate earthquake activity in the southeast. Seismic events in these regions are relatively small but occur with noticeable recurrence intervals of several years' duration. Minor structural damage occurs, but larger damages can be widespread with seismic magnitudes approaching 5.5. Much of the Atlantic Southeast can expect even lower peak ground accelerations within the next 50 years and, therefore, lesser chances of felt earthquakes. The expected values of acceleration, though, should prompt citizens in the areas of greater potential to ensure that foundations of houses and other buildings are adequately prepared to withstand the estimated potential motions. The least damage will occur to buildings underlain by consolidated rock. However, existing structures underlain by unconsolidated to semiconsolidated sediments, weathered rock, and thick soils should be reinforced as necessary to meet local building codes that have been established to meet the predicted seismic hazards.

Groundwater Issues (Hydrogeology)

Groundwater supplies at least 25% of the water for drinking in the Atlantic Southeast region. All of the groundwater in this region originates from precipitation including rain and snow. Average annual precipitation values range from as low as 30 inches/year to more than 80 inches/year. Groundwater is stored in rocks and unconsolidated deposits that comprise **aquifers**, or systems of aquifers, and **confining units**. A saturated rock or deposit that has enough space to hold water between the solid particles or minerals (called pore space) and that permits the free flowage of the water through the rock or deposit (often called permeability) defines an aquifer. Any saturated rock or deposit that essentially limits the flow or passage of water through it at extremely slow rates is a confining unit. Groundwater systems within a physiographic province consist either as layers of connected and mutually dependent aquifers or as a sequence of separate, unconnected, nearly identical aquifers that act as a single unit. Up to six aquifers, including a surface aquifer, are present within the Coastal Plain. Three aquifers within consolidated rocks, and an unconfined aquifer in overlying, unconsolidated surface deposits, define the groundwater system in the Piedmont and Blue Ridge. The Valley and Ridge and Plateaus contain two systems within consolidated strata, as well as a local, overlying surface aquifer.

Aquifer systems are at risk for contamination from two general sources: direct infiltration by contaminated surface and near-surface waters; and direct recharge of contaminants into the aquifer by injection, leaky wells, and other faulty structures. Very slow velocities and nonturbulent flow of groundwater allow narrow plumes of contamination from spreading laterally and undergoing natural purification. In areas of low population density, practical methods of remediation do not require much more than time and a new well. However, urbanization and industrialization in concentrated areas has created more complex problems requiring more significant efforts at remediation including excavation and transportation of contaminant soils. Actions and regulations may call for actual "cleaning" of the groundwater by a combination of pumping, filtration, extraction, or introduction of catalysts, which can cause a rapid breakdown of the contaminating agents within the groundwater. Practical solutions may also call for installation of municipal sewer systems and water supplies in place of individual septic systems and wells. Sources of contaminants in the Atlantic Southeast region include improperly functioning septic systems; leaking sewer pipes, mechanical breakdowns of municipal sewer systems, or both; industrial and chemical wastes leaking from storage facilities; pesticides and fertilizers applied to crops; and excessive withdrawals of groundwater leading to saltwater invasion of freshwater aquifers in coastal regions.

Climate Changes and Eustatic Sea Level

Exposures of peat and mud typical of back-barrier island deposits, tree roots and stumps, and many other occurrences of similar oddities indicate that sea level is currently rising. Tidal records of elevations from around the world demonstrate a consistent fractional increase in sea level each year for at least the past 100 years. The obvious cause for this rise is melting of continental glaciers in the past 10,000 years as the Earth's climate has warmed. Pleistocene glaciation repeatedly affected the globe with at least 20 cycles of cooling and warming as recorded by oxygen isotope and carbon dioxide data from terrestrial and marine sources. Preserved marine terraces and transgressive cycles recorded a history of cyclic changes of **eustatic sea level** throughout the Tertiary in Coastal Plain strata. Although the record of multiple cycles of warming and cooling is clear, explanations for the variation of climate are not in agreement. However, for our purposes, the main concern of climate change is its effect within the coastal zone. Regardless of causes leading to warming and predictions of how much warming will occur, processes in the coastal zone are greatly modified even with relatively small changes in sea level. As sea level rises, shorelines and barrier islands move progressively landward. The gentle angle of slope on the continental shelf results in a larger amount of lateral migration per small elevation in sea level; that is, the rise of sea level is balanced by a very large run of the shoreline over land areas. Barrier islands migrate by the action of littoral currents, overwash, and inlet migration. This means that sand on the beaches must shift position and fill inlets as the island slowly creeps landward. Anything that lies in the pathway of migration is affected, including the actions of humans. Our society can follow a responsible path of adjustments to the migration of barrier islands and beaches that minimizes expenses and inconveniences presented by this natural process. Disagreements on possible causes and catalysts of global warming only postpone our ability to establish practical adjustments for a large population exposed to the risks of rising sea level. Inhabitants of coastal zones must remain diligent to short- and long-term changes in sea level. Human activity must also institute and maintain actions and plans that minimize our obstructions to coastal zone processes that are responding to changing sea levels.

The coastal areas of the Atlantic Southeast region currently experience high levels of interest for tourism, commercial development, and urbanization. Many activities prove to be at odds with the concentrated energy of dynamic coastal processes, and this leads to many conflicting interests and policies. "Starving" the beaches from receiving sand includes damming of rivers or creating obstacles and obstructions to the littoral and barrier systems. Attempts to control the movement of littoral sand and sediment often have led to a net loss of sediment in the system, which, in turn, leads to more erosion. Large tropical storms can move much sediment from the shoreline, but subsequent daily processes can restore this sand onto the beach. Seasonal storms such as nor'easters can create as much erosion, if not more, and the system takes longer to repair itself. Until all of the local populations are fully aware of the hazards created by development in coastal areas—the problems of erosion of sand coupled with migration of barrier islands onshore as an effect of rising sea level—policies that promote more accommodations to the natural dynamics of the system will never gain acceptance.

Tropical Storms, Floods, and Mass Movements

The Atlantic Southeast region routinely experiences the effects of tropical storms generated within the Atlantic Basin, including the Gulf of Mexico and Caribbean Sea. High magnitude, but relatively infrequent, storms produce catastrophic destruction over large areas by devastating winds and flooding. High amounts of rainfall associated with large, slow-moving tropical systems effectively drown principal streams of major drainage basin, which results in backing up and overflowing of tributary streams within the basin. Floodwaters in the lower reaches of a drainage basin can last for weeks before flowage lowers the levels below flood stage. Storm surge associated with a given storm affecting a coastal region may exceed the maximum elevation of a protective dune field, thereby flooding low-lying areas behind the barrier. Over the past century in the southeastern United States, improved construction, planning and zoning practices, and improved analyses and predictions of tropical storms have resulted in fewer deaths from tropical storms. Drastic increases in costs related to physical damages to structures from storm-driven wind and rains over the same time interval, however, reflect an increasing population in the coastal zone, and given the decadal or longer episodic cycle of high-magnitude storms, prompts officials to levels of emergency planning and response that exceed historical levels.

Regions within the southeast outside of the Coastal Zone also experience the effects of tropical storm systems. Although hurricane force winds rapidly diminish as storms track inland, the systems are still capable of spawning tornadoes and producing copious amounts of rain. Widespread flooding can occur directly from the precipitation, as well as the damming effect on principal drainage streams when the entire basin is overwhelmed. Flooding in mountainous areas such as the Blue Ridge and Valley and Ridge is particularly hazardous because of flash-flood events and mass movements. Thick sections of unconsolidated regolith on steep slopes become saturated with heavy rains. Their growing instability leads to rapid downslope movements of the regolith as landslides or mudslides. Debris slides in western North Carolina associated with tropical storms in 2004 and 2005 made national news for the magnitude of their destruction. Widespread damage from mass movements in the mountains, though, is historical as written accounts in the early part of the twentieth century document debris flows and landslides attributed to slow-moving remnants of hurricanes and tropical storms. In addition to rainfall exceeding several inches, mass movements in the mountains are influenced by other factors including soils already saturated, human activities that provoke or initiate slope instability (clear cutting, for example), and the underlying geologic framework. Increased risks for widespread and frequent mass movements can only result as more of the mountainous areas within the southeast are developed as urban and recreation areas. Methods of careful planning and action plans should be followed to minimize the risks and adjustments to this natural hazard.

Tsunami Threats

The Banda Aceh earthquake and tsunami of December 2004 reminded the world of the severe levels of death and destruction associated with a tsunami. What is the potential for such levels if a tsunami struck the southeast region? The answer lies with understanding that a tsunami occurs in response to a sudden displacement of seawater related to rapid uplift or subsidence of the sea floor by faulting or from a submarine landslide pushing displaced water laterally in front of the moving debris. Destructive tsunamis correspond to major earthquakes whose Richter magnitudes greatly exceed 7.0, and by massive submarine landslides that involve tremendous volumes of debris. The relative dearth of large fault zones capable of suddenly raising or lowering the sea floor adjacent to the southeastern region of the United States precludes a destructive tsunami related to earthquakes. Within the Atlantic Ocean Basin, the Caribbean offers potential for larger earthquakes and faults capable of generating destructive tsunami affecting the Atlantic Southeast region, but the separation distance could limit the size of the waves reaching this region. Another threat for tsunami in the southeast is catastrophic collapse of volcanic islands in the Cape Verde chain. Models suggest that tsunami of several meters in height could travel and strike the East Coast from such a catastrophic collapse and landslide. Images of crowns, tracks, and toes of submarine landslides along our own continental margin and slope raise concerns about tsunami forming in this area. However, no information is available as to the actual time(s) of formation of these structures, which constrains predictions of events. Also, any tsunami created by landslides on our continental margin would travel eastward, which limits the impact of the event on the East Coast. An additional possible source for an East Coast tsunami is by a large meteorite or bolide impact in the Atlantic Ocean Basin. Variations in submarine topography may prevent catastrophic damage from tsunami in most East Coast settings by obstructing, diverting, and interfering with incoming waves. Chances are excellent that we will never experience a major tsunami along the southeastern coast in our lifetimes.

Environmental Concerns

Four general areas of concern raise issues related to environmental degradation within the Atlantic Southeast region: coastal resources, hydrologic resources, waste disposal and septic issues, and urbanization. Although all of these areas overlap with each other, none is completely evaluated unless the underlying geology is known and understood.

Urbanization is the overriding umbrella for most environmental problems in the region. The region hosts major cities and ports of the eastern seaboard, as well as alluring beaches and other natural areas that invite the attention of locals and visitors. The popularity of the region to many people places an ever-increasing demand for real estate, transportation, utilities, and other resources, each of which carries a complex and burgeoning infrastructure. Deciding the best location of a new road, intersection, or bridge is a critical task, but equally important are issues concerning the locations of materials needed for their construction, potential loss of other resources by paving over them, and the potential contamination effects of storm water runoff into adjacent soils, wetlands, streams, and estuaries. The location of the coastal zone and plain is really an important transition between the naturally dynamic environments of the marine and terrestrial realms. We now understand that the subsurface below many areas of the land are records of changes and transitions between environments through time. Their vertical succession downward is a useful guide to lateral changes or disruptions in buried layers. Just as our effects on land are significant, so, too, are our efforts below the land surface. We must always ensure that we have the best information available for both the surface and subsurface materials for any project that is proposed. Not to do so is unethical and poor stewardship for successive generations.

Hydrologic resources are vital to urbanization. Hydrology includes both surface water and groundwater systems in this case. Rivers continue to provide a major source of freshwater for consumption by people, industry, and agriculture, and groundwater resources are becoming significant additional resources. A natural system of cleansing or purifying both surface and groundwater resources lies within soils and wetlands adjacent to streams and overlying recharge areas of aquifers. The term *wetland* actually refers to particular relations among soil type, soil moisture, and the water table. Urbanization must remain vigilant in correctly identifying and protecting wetland areas for protecting water resources, as well as natural living environments and ecosystems that promote the pleasing aesthetics of the region. Protection of wetlands and soils overlying unconfined and **confined aquifers** is critical because remediation of contaminated aquifers is expensive, time-intensive, and difficult. As surface water becomes unusable for any number of reasons, some urban areas are turning to aquifers for additional water to meet their needs. This need places heavy demands on aquifers, and care must be taken to ensure that natural recharge can keep pace with the volume of water mined or extracted. If excessive water is withdrawn from an aquifer, the porosity and conductivity can be lost and never recovered. Similar hydrologic issues occur in more consolidated bedrock in the uplands and mountainous areas of the southeastern region. One significant difference in aquifer systems of crystalline rocks is the thickness of regolith overlying the aquifer. The regolith effectively exists as an unconfined aquifer that recharges the fracture porosity of the underlying crystalline rocks. Disturbance of the regolith can significantly affect the health of the aquifer. Aquifer systems in the Valley and Ridge and Plateaus include geologic frameworks that are similar to the preceding discussions. Any plans to use these precious resources to meet increased needs of urbanization, commerce, and agriculture must be balanced by wise decisions, timely methods, and ethical concerns for prolonging the useful life of the water resource.

People cannot live without generating wastes. Waste disposal issues are pervasive in urban areas. Environmental problems result if the conditions existing within disposal sites cannot decompose the wastes completely before entering the environment. Landfills are engineered excavations where solid waste is buried daily in specific cells or small areas of the excavation. Rainfall and surface moisture can infiltrate into the cell despite preventative measures including a cap of relatively impermeable soil over the cell. These waters percolate downward, partially leaching decomposing wastes, and enter the ground as leachate. Insufficient thicknesses of soil between the base of the landfill and the water table leachate to enter an aquifer system. Lining the base of landfills with thick impermeable media such as plastic sheeting has become a practical means of reducing leachate for new landfills, but remediation of leachate contamination at older sites often include shutting down the entire operation. If potable water supplies have been damaged by contamination, then new supplies are found after significant effort and expense. Contamination of surface and groundwater supplies by septic tank systems is similar to the leachate problems with landfills, although the scale is different. One solution for failing septic tanks and contamination of groundwater is to install a municipal water and sewer system. This is not a foolproof solution, though, because numerous examples of breaks in sewer lines dumping millions of gallons of raw sewage into stream, estuaries, or city streets can be found in the archives of many urban newspapers.

Review Workbook

SUMMARY

Atlantic Southeast.1 Introduction

■ *Why aren't active volcanoes present within the Atlantic Southeast region despite a record of seismic activity?*

The current tectonic setting of the Atlantic Southeast region is that of a passive margin. Passive margins do not involve either active rifting or subduction, both of which trigger partial melting of the mantle and crust, a critical component in the formation of magmas. Moderate earthquake activity within the region results from intraplate stresses interacting with older tectonic features.

■ *How has the geology of the Atlantic Southeast region contributed to the economic history of the United States?*

The first gold rush occurred in central North Carolina in the earliest 1800s when the country was barely 20 years old. Iron ores, coal, and limestone in the Valley and Ridge and Plateaus were the essential ingredients for the steel industry of the United States. Other resources in the various parts of the Appalachians have provided nonmetallic mineral and rock deposits, raw materials, and sources of energy for many industries across the nation.

Atlantic Southeast.2 Proterozoic Geology and Tectonics

■ *What events led to the formation of Rodinia?*

Rodinia was an early supercontinent that formed by continent–continent collisions of all the world's continents during the Proterozoic. The Grenville Orogeny is one of the processes that led to Rodinia and represents thrusting and stacking of thrust plates involving segments of the lower continental crust, a process similar to that of the Himalaya Mountains.

■ *What evidence exists for interpreting a continental rifting event along the margin of Laurentia in the Late Proterozoic?*

Metamorphosed, thick, stratified sequences of conglomerate, arkosic sandstone, quartz sandstone, mudrock, and basalt dikes, sills, and flows unconformably overlie Grenville basement rocks and are bordered by a fault system. Younger Paleozoic strata overlie the Late Proterozoic stratified rocks. The stratified sequences are discontinuous along strike and tend to be narrow.

Atlantic Southeast.3 Late Proterozoic Climates, Paleogeography, and Life

■ *What is the significance of glacial climates in both Laurentia and peri-Gondwanan exotic terranes during the Late Proterozoic?*
The peri-Gondwanan terranes were separated from each other and Laurentia by the Iapetus Ocean. For these separated areas to have experienced identical glacial events requires an extremely cold global climate that supported continental glaciation.

Atlantic Southeast.4 Early Paleozoic History of the Laurentian Continental Margin

■ *What was Iapetus, and where was it located?*
Iapetus was an ocean that formed during the Late Proterozoic when Rodinia broke apart into Laurentia, Gondwana, and various chips and microcontinents. Iapetus was the ocean that existed between Laurentia and Gondwana.

■ *How do the Early Paleozoic strata of the Laurentian continental margin differ from the underlying Late Proterozoic stratified rocks?*
The Early Paleozoic strata of the Laurentian continental margin consist of a basal section of coarse-grained fluvial and transitional clastic sediments overlain by a thinner sequence of shale and mature quartz sandstones. A thicker interval of carbonate rocks caps the sequence. A few basalt flows occur within the lowermost parts of the basal clastic interval. Overall, the Early Paleozoic strata are much thinner and cleaner marine sediments compared with the significantly thicker and immature clastic rocks comprising the Late Proterozoic stratified rocks.

Atlantic Southeast.5 Proterozoic and Early Paleozoic History of the Terranes Comprising the Piedmont

■ *How does the geologic history of an exotic terrane that existed within the Iapetus Ocean marginal to Gondwana differ from that of Laurentia?*
The exotic terranes of the Iapetus Ocean basin reveal a history of docking events that occurred no later than the Cambrian. During this same time, the Appalachian side, Laurentia, was a drifting passive continental margin.

■ *What evidence exists that demonstrates the size of Iapetus?*
Rare fossil occurrences in some of the eastern Piedmont terranes indicate affinities with fauna that are found in terranes and continents known to have existed on the other side of Iapetus from Laurentia. Some of the terranes have isotope ratios in their basement rocks that group with the basement rocks and isotopes of Gondwanan continents. The composite nature of many Piedmont terranes documents a Proterozoic and Early Paleozoic history of docking and collision events that are not recorded along the margin of Laurentia, which is another argument in favor of a large ocean basin.

Atlantic Southeast.6 Middle Ordovician through Late Paleozoic Geology and Tectonics

■ *What events comprise the Taconic Orogeny?*
The Taconic Orogeny resulted from the attempted subduction of eastern Laurentia below a large composite terrane (the Piedmont). Rapid erosion and deposition of clastic sediments from the approaching Piedmont terrane filled up the trench and overflowed on the passive continental shelf of Laurentia. Together with a preceding uplift of the margin, the flooding of the continental shelf below the clastic wedge from the east buried the carbonate bank of reefs that had dominated the continental shelf throughout most of the Cambrian and Early Ordovician. The subduction event also accreted terranes with continental basements to Laurentia together with thrusting and shearing, intense metamorphism, and magmatism.

■ *What events comprise the Acadian Orogeny?*
The Acadian Orogeny in the southern Appalachians was a time of pervasive deformation related to dextral shearing along a transpressive boundary. Subduction processes were essentially absent. Regional metamorphism was relatively low. Devonian plutons of granitic rock are present as relatively small but abundant bodies within some geographic areas.

■ *What events comprise the Alleghanian Orogeny?*
The Alleghanian Orogeny consists of the events related to the ultimate closure of Iapetus when Gondwana collided with Laurentia. The collision resulted in widespread thrusting of deeper parts of the accreted Piedmont terranes over shallower parts of the Laurentian crust. The folding and thrusting of the Valley and Ridge formed at this time. Widespread metamorphism and granitic intrusions occurred throughout many of the composite Piedmont terranes.

Atlantic Southeast.7 Mesozoic and Cenozoic Geology and Tectonics

■ *What is a rift-to-drift sequence?*
A rift-to-drift sequence begins with a base of very coarse clastic sedimentary rocks and basaltic igneous rocks of continental rift basins. Overlying this base is a sequence of marine clastic rocks and overlying carbonates. The marine strata become part of a transgressive sequence that crosses the continental shelf onto a subsiding continental margin.

■ *Why do some rift basins have strata dipping northwest while others have strata dipping southeast?*
The strata accumulate in the basin as faulting progressively opens the basin. Border faults of the basins occur on either the northwest or southeast side. As northwest border fault dips southeast, then the strata will dip northwest toward the border fault. The opposite is true for southeast border faults.

Atlantic Southeast.8 Natural and Anthropogenic Hazards of the Atlantic Southeast Region

■ *What current natural hazards facing the population of this region today pose the greatest threats to property and life?*
The greatest threats are tropical storms and their associated high winds, storm surge, tornadoes, mass wasting in areas of higher relief, and extensive flooding.

■ *What are the chances of Myrtle Beach, South Carolina, and Virginia Beach, Virginia, being destroyed by a catastrophic tsunami?*
Very little because the tectonics that result in catastrophic tsunamis are not active around the East Coast of North America. We are so far distant from any active sources that natural attenuation of the tsunamis should prevent them from striking with catastrophic effects. Exceptions, of course, are meteorite or bolide impacts in the adjacent waters of the Atlantic, but none is expected within the near future.

ESSENTIAL TERMS TO KNOW

Acadian – a Devonian-aged orogeny in the southern Appalachians characterized by dextral strike-slip faulting, low-grade regional metamorphism, and intrusion of granitic rock.

accretionary complex – a wedge-shaped pile of mixed rock types that accumulates in front of the plate overlying a subduction zone by off-scraping and underplating of rocks from the descending slab to the base of the upper plate.

Alleghanian – a Late Paleozoic orogeny in the southern Appalachians characterized by thrust faulting, folding, regional metamorphism of upper amphibolite facies, late-stage dextral strike-slip faulting, and widespread granitic batholiths and smaller intrusions.

Appalachian orogenic belt – a linear range of mountains, valleys, plateaus, and piedmont uplands, and the rocks contained within, that extends from Alabama through Newfoundland. The Appalachians formed from a series of tectonic events in the Paleozoic Era.

aquifer – a porous and permeable rock that is saturated with groundwater and is capable of producing sufficient quantities for use.

basalt – the most common type of mafic volcanic rock. Oceanic crust consists of basalt. Continental rift basins also have basalt as lava as well as dikes and sills (properly called diabase).

batholith – a very large pluton composed of granite. Granite forms at convergent plate boundaries during orogenic events.

composite terrane – an exotic or suspect terrane that has formed by the docking of smaller terranes.

confined aquifer – an aquifer overlain by an impermeable layer of rock.

confining unit – the name of the impermeable layer of rock overlying an aquifer.

convergent plate boundary – the boundary between two colliding lithospheric plates where the directed motion is oriented at a moderate to high angle to the boundary.

disconformity – a type of unconformity between two sedimentary rock units sharing a common primary stratification; the unconformity is more or less parallel to the primary stratification.

docking – a term for the welding of two tectonic terranes, or a terrane and a continent, into one object.

drift sequence – refers to the mature marine strata that overlie and bury continental strata in rift basins; part of a passive continental margin.

ductile deformation – minerals and rocks lose their size and shape becoming distorted as the result of excess straining of the rock to applied stresses. Ductile deformation commonly occurs when the rock is warm enough to deform without shattering into fragments.

eustatic sea level – another name for global sea level; a reference level or datum for worldwide correlations of strata.

exotic terrane – a terrane whose original location is known.

forearc – a general term referring to rocks and accumulating immature sediments that occur in front of the volcanic arc region and behind the accretionary complex of a subduction zone in a convergent plate margin.

Grenville – a Proterozoic orogenic event affecting the eastern side of Laurentia.

Gondwana – the name of the large continent consisting of Africa, South America, Antarctica, and Australia; rifted apart from Laurentia during the breakup of Rodinia in the Late Proterozoic.

granite – a felsic plutonic rocks consisting of an equal mixture of potassium feldspar, plagioclase feldspar, and quartz. Granite is a common pluton found in orogenic belts and is the most common felsic plutonic rock in continental crust.

Iapetus – the ocean that formed in the Late Proterozoic between Laurentia and Gondwana. The closing of Iapetus occurred during the Paleozoic and is responsible for the orogenic activity in the Appalachians.

Laurentia – a former continent contained within the present continent of North America. Laurentia was part of the supercontinent Rodinia that broke apart in the Late Proterozoic. The Appalachian orogenic belt formed along the eastern margin of Laurentia.

magmatic arc (volcanic arc, plutonic arc) – a curved trend of magmatic activity that parallels and commonly sits behind subduction zones and deep-sea trenches at convergent plate boundaries.

microcontinent – a relatively small landmass or large island with a basement of continental crust. Microcontinents originate in several ways including fragments created by rifting of larger continents.

orogen – a linear zone of rocks that exhibits a history of crustal mobility and active tectonics. Orogens typically consist of a core containing high-grade metamorphic rocks, granites, and shear zones. Linear zones of lesser deformed and metamorphosed rocks commonly occur between the core of the orogen and its perimeter.

Pangaea – the supercontinent that formed during the Late Paleozoic. The collision of Gondwana with Laurentia that resulted in the Alleghanian Orogeny was one of the global collisions that formed Pangaea.

passive margin – an area of relatively quiet tectonic activity that occurs along the trailing edge of a drifting continent. Continental weathering, erosion, and deposition by rivers and streams characterize the clastic sediments of a passive margin. Carbonate sedimentation results from the chemical precipitation of dissolved ions in the marine waters overlying the passive margin.

regression – the process of lowering of relative sea level. Regressions occur on continental margins as relative sea level falls, or as the adjacent land mass rises, or both.

rift basin – a linear basin that is bordered by a normal fault on one side. Rift basins form from the thinning and extension of continental crust by rising heat from below associated with a mantle plume. Rift basins have relatively high margins and steep slopes where alluvial fans accumulate. Interior drainages in the central areas of rift basins contain lakes where evaporite deposits may form around the edges.

Rodinia – the supercontinent that formed in the Middle Proterozoic and broke apart in the Late Proterozoic. Rodinia's breakup provided the setting for Paleozoic orogenic events in the Appalachians.

shear zone – a general name for a zone of similar faults. Commonly, shear zone is associated with ductile deformation.

stitching pluton – an igneous intrusion along a terrane boundary that penetrates through both terranes and has the same relative age as the terrane boundary.

strike-slip fault – a type of fault motion characterized by separation parallel to the trend (strike) of the fault.

subduction zone – an inclined zone at a convergent plate boundary along which the lithosphere is pulled and pushed downward toward the mantle under an overriding continent or terrane. Magmas can form above subduction zones and rise upward through the crust to feed plutonic or volcanic arcs. Deep-sea trenches coincide with the upper end of subduction zones. Accretionary complexes and forearc basins occur behind the trench and in front of the volcanic arc in subduction zones.

suspect terrane – a terrane whose original location is not known for certain.

suture zone – a terrane boundary that has been stitched together.

Taconic – the name of the middle Ordovician Orogeny in the Appalachian Orogenic belt. The eastern margin of Laurentia was partially subducted below a composite terrane represented by the Piedmont.

terrane – an area within an orogenic belt that is bounded completely by faults and has a unique assemblage of rocks with distinctive characteristics that reflect an origin in a distant or different location external to the orogen.

transform plate boundary – a plate boundary characterized by directed motion more or less parallel to its length.

transgression – the process of rising of relative sea level. Transgressions occur on continental margins as relative sea level rises or as the adjacent land mass subsides, or both.

transpression – a combination of reverse faulting and strike-slip faulting. Transpression commonly is associated with transform plate boundaries.

unconformity – a type of depositional contact between rock units along which is a significant missing interval of time as the result of erosion, nondeposition, or both.