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By D. W. RANKIN, T. W. STERN, JAMES McLELLAND,
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CORRELATION OF PRECAMBRIAN ROCKS OF THE UNITED STATES AND MEXICO

Edited by J. E. HARRISON and Z. E. PETERMAN

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Lithology, distribution, correlation, and isotope ages of exposed Precambrian rocks in Eastern United States

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CORRELATION CHART FOR PRECAMBRIAN ROCKS OF THE EASTERN UNITED STATES

By D. W. RANKIN, T. W. STERN, JAMES MCLELLAND[1], R. E. ZARTMAN, and A. L. ODOM[2]

ABSTRACT

In the Eastern United States, Precambrian rocks are exposed in the Adirondack massif and in the Appalachian orogen. Rocks dated at 1,300–1,000 m.y. occur as outliers of the Grenville province of Canada. These rocks constitute a western basement to the Appalachian orogen and appear in the Adirondack massif, in anticlinoria along the Blue-Green-Long axis, and in gneiss domes farther east. The Chain Lakes massif in Maine, about 1,500 m.y. old, may represent a different block of continental crust. Rifting of the Grenville continental mass, accompanied by anorogenic igneous activity, began about 820 m.y. ago.

An eastern basement (750–650 m.y. old) has been identified in the Avalonian zone of the Appalachian orogen in southeastern New England. It is intruded by calc-alkaline granitic rocks roughly 600–640 m.y. old that are nonconformably overlain by Lower and Middle Cambrian strata. Extensive Precambrian stratified rocks (mostly younger than 610 m.y. but possibly including rocks as old as 725 m.y.) crop out in the Carolina volcanic slate belt and probably in the higher grade metamorphic belt east of that. These rocks include large volumes of felsic volcanic rocks and probably were deposited on a continental crust.

The eastern terranes were sutured to ancestral North America during the Appalachian orogenic events that closed the Iapetus Ocean basin. The location of the suture is uncertain, but it probably lies just east of the gneiss domes containing rocks older than 1 b.y.

INTRODUCTION

Precambrian rocks are exposed in the Adirondack Mountains, N.Y., in the core of a large dome flanked by lower Paleozoic sedimentary rocks. These high-grade metamorphic and intrusive rocks are contiguous with similar rocks of the Grenville structural province in Canada.

The Eastern United States is dominated by the Paleozoic Appalachian orogen, the product of collisional events between at least two continental masses. Differences between the Cambrian fauna on opposite sides of the orogen are important evidence for the former existence of an ocean basin called Iapetus, between the two flanks. These Cambrian faunal realms are referred to as Pacific or *Ollenelus* on the west and as Acado-Baltic or *Paradoxides* on the east (Theokritoff, 1968; Wilson, 1969). Oceanic crust is preserved as ophiolites within the lower Paleozoic rocks.

Rocks stratigraphically beneath Lower Cambrian strata are recognizable on each flank of the orogen. A pre-Appalachian crystalline basement consists of rocks metamorphosed by, or formed during, pre-Appalachian orogenic events. In the Adirondack massif and along the Blue-Green-Long axis, these rocks have isotopic ages typically ranging from 1,250 to 1,000 m.y. old. Along the eastern margin of the exposed Appalachian orogen in southeastern New England, the crystalline basement is dated as 750–650 m.y. old. An eastern basement has not been identified with certainty south of the Potomac River.

In places along the western margin of the Appalachian metamorphic belt (the Blue-Green-Long axis), a thick-to-thin sequence of stratified rocks lies unconformably on Precambrian crystalline basement and is overlain conformably by fossiliferous Lower Cambrian strata. These upper Precambrian and overlying Cambrian stratified rocks are interpreted as marking the ancient eastern continental margin of North America and recording the breakup of a larger continental mass by rifting and the formation of the Iapetus Ocean basin (Rankin, 1975). Prominent bends in the structural trends of the Appalachian orogen are thought to be inherited from the irregularities developed at the time of this late Precambrian continental breakup (Rodgers, 1975). Because upper Precambrian or Eocambrian rhyolites are restricted to three bends convex toward the craton, Rankin (1976) suggested that the bends developed at triple junctions over hot spots. Thomas (1977) amplified Rodgers' (1975) suggestion that the irregularities originated as a rift broken by transform faults. He called the bends that were convex toward the craton reentrants, rather than salients, and the bends that were concave toward the craton promontories, rather than recesses.

As a framework in which to discuss the Precambrian rocks, we accept that a rifting event in late Precambrian–early Paleozoic time created an ocean basin (Iapetus) in eastern North America. The ocean basin probably developed to the east of a series of early ensialic rifts, much as the present Atlantic opened to the east of the earlier ensialic Late Triassic–Early Jurassic rifts still exposed in eastern North America. The Appalachian orogen was formed by the closing of the Iapetus Ocean basin and the subsequent continent-continent collision. The

[1] Colgate University, Hamilton, NY 13346
[2] Florida State University, Tallahassee, FL 32306

continental mass that collided with the North American craton, however, may not have been the same continental mass that separated during the formation of the Iapetus Ocean. The location of the suture between the continental masses is one of the unresolved problems of Appalachian geology. The Adirondack massif is entirely west of the area affected by Appalachian (Paleozoic) metamorphic events. Potassium-argon mica ages from the Adirondacks reflect uplift and cooling following metamorphic events $\geq$ 1 b.y. ago.

The metamorphic and deformational history of the Appalachian orogen is complex, commonly polyphase. The grade of Paleozoic metamorphism increases eastwardly into the Appalachian orogen from little-recrystallized rocks of the Valley and Ridge belt and western Taconide zone to grades as high as sillimanite along the Blue-Green-Long axis (see Morgan, 1972; Zen, 1974). This westernmost Paleozoic metamorphism is of Ordovician age (about 430–460 m.y. ago) and is related to the Taconic orogeny.

In New England, the Taconic metamorphism is overprinted to the east by a later Acadian event (about 380–400 m.y. ago), and rocks as young as Early Devonian are metamorphosed to grades as high as sillimanite-potassium feldspar. Because fossiliferous rocks younger than Ordovician have not been identified in the crystalline Appalachians south of the New Jersey Highlands, the presence of an Acadian event is less easy to identify in the central and southern Appalachians. Nonetheless, polyphase metamorphism and isotopic ages suggest that a younger event roughly coeval with the Acadian also occurred in the Blue Ridge, Inner Piedmont, and Charlotte belt (see Butler, 1972; 1973).

The area comprising Rhode Island, eastern Connecticut, and southeastern Massachusetts forms a distinctive block separated from the rest of New England by a major fault system. This block, which contains the Acado-Baltic faunal province, shows no conclusive evidence of either the Taconic or Acadian metamorphic events. In southwestern Rhode Island, rocks as young as Pennsylvanian have been buried and deformed at staurolite and kyanite grade before crystallization of sillimanite by contact metamorphism adjacent to the 276-m.y.-old Narragansett Pier Granite (Grew and Day, 1972).

The metamorphic history of the eastern part of the southern Appalachians is not well understood. The grade of Paleozoic metamorphism decreases eastward through the Carolina volcanic slate belt, suggesting that the axis of the orogen (the suture) lies to the west. Yet a terrane of medium- to high-grade metamorphic and plutonic rocks, the southeastern metamorphic belt, crops out to the east adjacent to the Coastal Plain overlap. Several postorogenic plutons in and adjacent to this belt from Virginia to Georgia yield ages of about 300 m.y. (Fullagar, 1971; Secor and Snoke, 1978). On the other hand, we cannot rule out that parts of the southeastern metamorphic belt represent a higher grade terrane older than the Carolina volcanic slate belt; that is, an eastern basement.

Finally, the Coastal Plain of southwesternmost Georgia and northern Florida is underlain by nonfolded and nonmetamorphosed clastic rocks containing fossils ranging in age from Early Ordovician to probably Middle Devonian (Rodgers, 1970). These rocks have not been deformed by Appalachian orogenic events, and they contain a pelecypod fauna closely resembling that of central Bohemia and Poland but also with similarities to that of Nova Scotia, North Africa, and South America (Pojeta and others, 1976). Samples of crystalline rocks recovered from bore holes in Florida have yielded ages as old as 520 m.y. (Bass, 1969). These rocks, which may extend downward into the Precambrian, are not discussed further.

At least for that part of the Appalachian orogenic belt in which billion-year-old basement has been identified, the direction of tectonic transport was to the west or northwest. This Paleozoic transport may further complicate interpretation of Precambrian geology. Recent work by the Consortium for Continental Reflection Profiling (COCORP) suggests that the Blue Ridge and at least part of the Piedmont have been thrust westward at least 150 km in northeastern Georgia (Cook and others, 1979).

DESIGN OF THE CORRELATION CHART

The Appalachian orogen is characterized by subparallel relatively narrow belts differing in rock type, structure, and physiography. Some, but not all, of these belts are recognizable for the entire length of the orogen from Alabama and Georgia to Newfoundland. The correlation chart (pl. 1)[3] is organized as a traverse across these belts from the craton in the Adirondack massif to the opposite side of the orogen in the subsurface of Florida. These belts reflect the previously outlined plate-tectonic history; that is, the opening and closing of the Iapetus Ocean.

In constructing the chart, we have sought to consider *all* pertinent isotopic ages published through August 1979 and some unpublished ages. Ages shown in italics in the text (all ages on the chart) were calculated using the constants and abundances given in the introductory chapter of this report (Harrison and Peterman, in press). The recalculated ages are given to the nearest million years but do not necessarily imply that precision. The ages that appear opposite the time-rock columns on the chart are only Rb-Sr whole-rock isochrons or the upper intercept of U-Pb discordia curves. In general, the Rb-Sr whole-rock-isochron ages are given only for intrusive and extrusive igneous rocks or their metamorphic equivalents. If the same rock body has been dated by more than one method, both ages are indicated. This

[3]Synthesized stratigraphic columns to which the isotopic ages are tied are identified by circled capital letters on pl. 1. Related stratigraphic columns are indicated by subscripts. The generalized geographic locality of every constructed or synthesized stratigraphic column is shown on pl. 2 but because of space constraints not all are shown on pl. 1.

data set is the first attempt to portray all available ages using a fixed set of decay constants and abundances. We hope that the reader will recognize our intent to provide a consistent data set rather than immutable ages.

From a review of papers published by many authors over a considerable period of time, it is difficult to evaluate the analytical errors. Typically, a 2- to 3-percent uncertainty at the 95-percent confidence level can be expected for modern determinations. If the scatter of the data or the authors' assessment suggests an uncertainty of greater than 6 percent, the age is not given on the chart. For these determinations and for mineral ages and $^{207}Pb^{206}Pb$ ages (hereafter referred to as Pb-Pb ages), the position of the footnote number on the chart indicates the published age on the vertical axis (see pl. 1). Potassium-argon mica ages were used only for some pegmatites in the Adirondacks. We have used the subdivisions of the Cambrian suggested by the Holmes Symposium (Geological Society of London, 1964), with the base of the Cambrian at 570 m.y. The correlation chart, therefore, includes at least the lower part of Cambrian sections that are stratigraphically tied to Precambrian rocks.

GEOLOGIC-CHRONOMETRIC DATA

ADIRONDACKS

The Adirondack massif is a dome of multiply deformed Precambrian rocks that were regionally metamorphosed about 1 b.y. ago during the Grenvillian orogeny. A northeast-trending mylonite belt separates granulite facies rocks of the Adirondack Highlands (A_2) from the dominantly amphibolite facies rocks of the northwestern Lowlands (A_1) (pl. 2).

The Highlands and Lowlands consist of similar rocks: (1) a basal sequence of principally charnockitic quartzofeldspathic gneisses, (2) several sequences of stratified units including quartzites, marbles, calc-silicates, and quartzofeldspathic gneisses, (3) at least two thick and commonly massive units of quartzofeldspathic gneisses within the stratified sequences, and (4) metaigneous rocks of the anorthosite-charnockite suite and crosscutting pegmatites, granitic rocks, and olivine metagabbros. Group 2 dominates in the Lowlands, whereas groups 1, 3, and 4 dominate in the Highlands.

Isachsen and others (1975) suggested that the anorthosite intruded the stratified sequence. Walton and de Waard (1963) envisaged the anorthosites as part of a pre-"Grenvillian" basement upon which the stratified rocks were unconformably deposited. De Waard (1970) and de Waard and Romey (1969) presented evidence for a comagmatic evolution of all the rocks in the anorthosite-charnockite suite, although Buddington (1972) disputed these conclusions and favored separate intrusions of magma. Isachsen and others (1975) favor a crustal anatexis origin for the charnockitic rocks.

Silver (1969) reported a U-Pb zircon age of *1,111* m.y. for charnockites of the Ticonderoga dome and other localities. Textural evidence suggests that this age dates the time of crystallization of these charnockites and closely associated anorthosites. A slightly younger age of *1,070* m.y. obtained directly on Highland anorthosite and norite is interpreted to date the peak of granulite facies metamorphism in the region.

Hills and Gast (1964) determined a Rb-Sr whole-rock-isochron age of *1,071* m.y. for charnockites in the Lake George pluton, which may be either an intrusive age or a metamorphic age of strontium isotopic homogenization. Nearby paragneisses have similar, albeit poorly constrained, ages suggesting that such homogenization did occur on a large scale, at least in the eastern Adirondacks. Although Spooner and Fairbairn (1970) reported a Rb-Sr whole-rock-isochron age of *1,394* ± *444* m.y. on charnockites in the Snowy Mountain dome, Hills and Isachsen (1975) obtained an age of *1,173* m.y. on samples from the same locality.

Bickford and Turner (1971) obtained Rb-Sr whole-rock-isochron ages of *1,095* m.y. and *1,120* m.y. for rocks believed to be of anatectic origin from two granitic domes. These ages for the period of anatexis are indistinguishable from the age of metamorphism determined by Silver (1969). A paragneiss also dated by Bickford and Turner yielded an age of *1,184* m.y., which is only slightly older than the time of anatexis in this region. In general, investigators have found little geochronologic evidence supporting the concept of an older basement complex in the Adirondacks.

Several K-Ar ages of micas obtained from pegmatites are generally younger, in the range of 900 m.y.–1,000 m.y., and reflect cooling of this terrane following the major metamorphic events.

In southern Ontario, supracrustal rocks of the Grenville Supergroup lie unconformably on the 1,400- to 1,500-m.y.-old Algonquin batholith (Lumbers, 1979; written commun., 1979). Volcanic rocks within the carbonate sequence of the supracrustal rocks are dated at about 1,300 m.y. (Silver and Lumbers, 1966) and are related to intrusive rocks dated at about 1,280 m.y. Thus, evidence from Canada suggests that the Adirondack stratified rocks, at least those directly across the Frontenac axis in the Lowlands, accumulated 1,400–1,250 m.y. ago.

The Adirondack rocks are deformed by four major foldsets whose mutual interference determines outcrop patterns over large areas. High-grade metamorphism appears to have continued throughout F_1 and F_2 folding, at pressures corresponding to a depth of burial of 25 km. Because seismic studies by Katz (1955) indicate that, at present, the M-discontinuity is at a depth of 36 km, a crustal thickness of about 60 km for the Adirondacks is implied at the time of the orogenic event 1.0–1.1 b.y. ago. McLelland and Isachsen (1980) discussed two models for generating this double crustal thickness and the structural framework of the Adirondacks. Continental collison and some degree of continental underthrusting toward the northwest are involved in both models. They suggested that the New York–Alabama geophysical lineament of King and Zietz (1978) and the, as yet, undefined northeastern continuation may be the suture resulting from this continental collision (pl. 2). If that interpretation is correct, the billion-year-old suture is roughly parallel to Appalachian structures. In fact, we cannot rule out, at present, the possibility that the billion-year-old suture was even farther southeast along the same line now represented by the Taconian suture.

TACONIDE ZONE

The east-derived Taconic allochthon (B) of eastern New York and western New England consists of at least six structural slices that overlap eastward so that the highest structural level is at the eastern edge of the composite allochthon (Zen, 1967; Ratcliffe and others, 1975). Fossils from the allochthon range in age from Early Cambrian to Middle Ordovician. No Precambrian rocks have been dated isotopically, but a thick section of green and purple slate, graywacke, conglomerate, and minor quartzite (for example, the Nassau Formation) lies conformably beneath the West Castleton Formation, which contains Early Cambrian fossils. The Nassau is of inferred late Precambrian age and makes up a large part of the structurally higher slices. The Rensselaer Graywacke Member of the Nassau has been interpreted as a graben facies deposited during the initial opening of the Iapetus Ocean basin (Bird, 1975).

BLUE-GREEN-LONG AXIS

OLDER PRECAMBRIAN ROCKS

The older Precambrian rocks of the axis from the Reading Prong north to the Green Mountains more closely resemble the rocks of the Adirondack massif than do those farther south. These northern massifs include paragneiss, marble, calc-silicate gneiss, hypersthene leucogneiss, and syenitic and granitic gneiss with relatively minor clearly identifiable intrusive rocks. South of Pennsylvania, intrusive orogenic granitic rocks (quartz monzonite to diorite) predominate over paragneiss.

Along the western margin of the Blue Ridge where the Paleozoic metamorphic overprint is relatively minor, the older basement is comprised of both paragneiss and orthogneiss. Zircons from samples of paragneiss at Pardee Point, Tenn., and Deyton Bend, N.C. (pl. 2, D_{1a}), yield a discordia intercept age of *1,280* m.y. (Davis and others, 1962). Fullagar and Odom (1973) obtained a Rb-Sr whole-rock-isochron age of *1,225* m.y. for layered biotite-muscovite gneiss (Paleozoic amphibolite facies terrane) from central Ashe County, N.C. (J_1).

Although the older Precambrian orthogneisses constitute large masses along much of the Blue Ridge anticlinorium, toward the southwestern end they crop out only in the cores of smaller second-order folds within terrane of younger(?) layered gneiss and schist. The southwesternmost known areas of older Precambrian rocks are two bodies of foliated granite near Cartersville, northwestern Georgia (C_4), which dating confirms as being at least 1 b.y. old. Farther northwest in terrane of higher grade Paleozoic metamorphism, Kish and others (1975) report a 1.1-b.y. Rb-Sr whole-rock-isochron age from the augen gneiss in the core of the Bryson City dome (C_3). Above the Fries-Hayesville fault in northeastern Georgia, the Wiley (augen) Gneiss dated at about *1,190* m.y. old crops out in the cores of refolded folds around the Tallulah Falls dome (Hatcher, 1976) (I_1). The Toxaway Gneiss in the core of the Toxaway dome (I_2) has a Rb-Sr whole-rock-isochron age of about 1,190 m.y. (Fullagar and others, 1979).

Basement plutonic rocks in northwestern North Carolina were informally named the Elk Park plutonic group by Rankin and others (1973).[4] The protoliths of this orogenic calc-alkaline suite were fine-grained to coarsely porphyritic diorites to quartz monzonites. Stratigraphic names in common usage for these rocks include the Cranberry Gneiss (D_1, J_1) of the Blue Ridge thrust sheet in northwestern North Carolina and the Blowing Rock (augen) and Wilson Creek Gneisses (D_2) within the Grandfather Mountain window. The Max Patch Granite (C_3) of the Great Smoky Mountains is probably correlative. The name Grayson Granodiorite Gneiss (D_1) was retained by Fullagar and Odom (1973) for similar rocks in Grayson, County, Va., although Rankin and others (1972) preferred to extend the name Cranberry Gneiss into that area. Davis and others (1962) published zircon analyses from three samples of rocks of the Elk Park Plutonic Suite, and four additional samples of the unit not previously reported were collected by Rankin and analyzed by Stern. Although the seven rocks were collected from localities as far apart as 150 km—from the Blue Ridge thrust sheet, as well as the Grandfather Mountain window—the geologic interpretation is that the rocks are correlative and yield a pooled discordia intercept age of *1,079* m.y.

Fullagar and Odom (1973) published three Rb-Sr whole-rock-isochron ages for older plutonic rocks in northwestern North Carolina and vicinity. (1) A flaser gneiss phase of the Cranberry Gneiss from western Watauga County, N.C., and eastern Johnson County, Tenn., yielded an age of *1,041* m.y. (2) The Blowing Rock Gneiss yielded an age of *1,005* m.y. (D_2). (3) The Grayson Granodiorite Gneiss in the Blue Ridge thrust sheet in Grayson County, Va. (D_1), yielded an age of *1,149* m.y. and may be somewhat older than the other units.

[4]The Elk Park is herein adopted as a formal term and designated Elk Park Plutonic Suite.

The next large area of older Precambrian basement to the northeast forms the core of the Virginia Blue Ridge from Floyd County, Va., to near Frederick, Md., a distance of about 380 km (D_3, J_2). No unambiguous paragneiss unit has been identified in this part of the Blue Ridge anticlinorium. The assemblage of plutonic rocks, collectively called the Virginia Blue Ridge Complex, is much like those of the North Carolina Blue Ridge except that charnockitic rocks are more abundant. Tilton and others (1960) reported a Pb-Pb age of *1,130* m.y. for zircons from the hypersthene granodiorite at Mary's Rock Tunnel in Shenandoah National Park. Lukert and others (1977) gave unspecified zircon ages for rock units toward the north end of the anticlinorium core.

The next Precambrian massif to the northeast is the Reading Prong–Hudson Highlands. The southwestern end of the massif in Pennsylvania (E_1) is allochthonous (Drake, 1969). The northeast end, in New York and Connecticut (E_2), is probably parautochthonous (Harwood and Zietz, 1974). This latter terrane can be broken down further into the western and the eastern (Hudson) Highlands divided by the Ramapo-Canopus fault zone (Hall and others, 1975). The effects of Paleozoic deformation and metamorphism are much more intense in the eastern Highlands (Long and Kulp, 1962; Dallmeyer and Sutter, 1976).

The Reading Prong and western Highlands consist mostly of high grade quartzofeldspathic metasedimentary and metavolcanic rocks interlayered with smaller amounts of amphibolite and marble and associated with sodic granitic rocks, hornblende granite, and alaskite (Drake, 1969). Within the Reading Prong, Long and others (1959) obtained Pb-Pb ages on uraninite from a marble near Phillipsburg, N.J., and monazite from the Losee Gneiss near Chester, N.J., of *898* and *883* m.y., respectively. Many Precambrian rocks have been dated from the Hudson Highlands, and these results are summarized in table 1.

Rocks of the Housatonic Highlands lying stratigraphically beneath the Poughquag Quartzite (Hall and others, 1975) in western Connecticut have not been dated, but they are lithologically similar to those of the Berkshire massif and presumably of similar age.

The older Precambrian rocks of the Berkshire massif (F and K) are largely quartz and feldspar-rich graphitic and nongraphitic metasedimentary rocks and lesser amounts of felsic and mafic metavolcanic rock and one distinctive calc-silicate unit (Ratcliffe and Zartman, 1976). A distinctive blue-quartz-bearing graphitic gneiss and biotite gneiss, the Washington Gneiss, is intruded by coarsely blastoporphyritic Tyringham Gneiss in broadly concordant sills. The Berkshire massif is allochthonous and was transported at least 21 km from the east at the time of Taconic metamorphism. Uranium-lead ages for zircons from the Washington Gneiss and Tyringham Gneiss are only slightly discordant, and the intercepts of discordia lines are *1,022* and *1,060* m.y. Ratcliffe and Zartman (1976) favored the interpretation that either the Tyringham Gneiss was intruded during the same dynamothermal event that reset the Washington Gneiss zircons or that the zircons from both the Tyringham and Washington Gneisses record a metamorphic age. Mose (1975; written commun., 1980) determined a Rb-Sr whole-rock-isochron age of *1,045* ± *128* m.y. for the Tyringham Gneiss.

The older Precambrian rocks of the Green Mountain massif (G and L) were collectively called the Mount Holly Complex by Doll and others (1961). The complex consists largely of fine- to medium-grained biotite gneiss, locally muscovitic, massive and granitoid in some areas, and compositionally layered in others. Amphibolite, hornblende gneiss, mica schist, quartzite, calc-silicate granulite, and marble are present, as well as numerous bodies of pegmatite and foliated granitic rock. Except for a Rb-Sr age of *1,047* m.y. on muscovite from a pegmatite at Buttermilk Falls (Naylor, 1975), the only pertinent age determinations are lead-alpha determinations (Faul and others, 1963).

STRATIFIED ROCKS ALONG THE BLUE-GREEN-LONG AXIS

At placed along the western flank of the Blue-Green-Long axis, thick sections of stratified rocks are present

TABLE 1.—*Ages of rocks from the Hudson Highlands*

Recalculated age (m.y.)	System used	Number of samples if known	Reference (footnote number from pl. 1)	Rock type
West of or along the Ramapo-Canopus fault zone				
913 ± *90*	Rb-Sr	7	17	Partial melt from paragneiss of the Canada Hill type
996 ± *94*	Rb-Sr	4	55	Late tectonic alaskite
1,106 ± *90*	Rb-Sr	12	55	Hornblende-granite gneiss at Bear Mountain
1,068 ± *40*	Rb-Sr	6	41	Canopus diorite-monzonite pluton
1,147 ± *86*	Rb-Sr	7	17	Paragneiss at Bear Mountain
1,139 ± *50*	Rb-Sr	13	55	Metavolcanics west of Bear Mountain
1,149 ± *45*	U-Pb	2	50	Storm King Granite and Canada Hill Granite Gneiss
East of Ramapo-Canopus fault zone				
1,281 ± *196*	Rb-Sr	4	55	Reservoir Granite Gneiss, J series
1,225 ± *60*	Rb-Sr	10	55	Reservoir Granite Gneiss, R series

between the fossiliferous Lower Cambrian rocks and the 1.0- to 1.3-b.y.-old basement. Only a few of the stratified rocks have been dated isotopically. The available time interval for formation of many of the stratified rocks is about 500 m.y. Fossils have not been identified on the east flank, so that the younger age limit, other than by very long distance correlation, is really established only by the age of the Paleozoic metamorphism or intrusive rocks.

WEST LIMB

The Talladega Group (C_1) is a thick section of weakly metamorphosed mostly fine-grained clastic rocks that crop out in Alabama and Georgia southwest of Cartersville, Ga. (Alabama Geological Society, 1973). The group is coextensive with the Talladega block, bordered on the northwest by sedimentary rocks of the Valley and Ridge province and on the southeast by the metamorphosed stratified rocks of the crystalline Appalachians. The block appears to be bounded in Alabama on both sides by northwest-directed thrust faults (Tull, 1978). Most of the Talladega terrane is unfossiliferous, although the Jemison Chert at the extreme southwestern end of the block contains Early Devonian fossils. The relation of this unit to the rest of the Talladega Group has not been established. One traditional interpretation is that these rocks are, at least in part, correlative with the Ocoee Supergroup (see Hadley, 1970).

The Ocoee Supergroup is a great mass of volcanic-free clastic sedimentary and metasedimentary rocks that crop out over a large area from Cartersville, Ga., northeastward along the Tennessee-North Carolina border to the Nolichucky River gorge, a distance of about 290 km. The supergroup extends across strike about 100 km and is present in several major tectonic units separated by thrust faults. The total thickness of the Ocoee has been estimated as 12 km (Hadley, 1970), and as much as 7 km of section are present in a single thrust sheet (Rodgers, 1972). The great thickness of the Ocoee and the evidence for rapid deposition suggest accumulation in one or more large block-faulted basins. The Ocoee Supergroup is considered to be of Precambrian age although no pertinent isotopic ages are available from it. Along the northwest edge of the Great Smoky Mountains (C_{2a}), the Sandsuck Formation, defined as the upper unit of the Walden Creek Group, is overlain, with no obvious discordance, by the basal Cochran Formation of the Chilhowee Group.[5] Early Cambrian ostracods occur in the upper part of the Chilhowee Group (Murray Shale) in the foothills belt of the Smokies.

[5]Note added in press. Knoll and Keller (1979) report morphologically distinct and stratigraphically useful acritarchs from three formations spanning most of the Walden Creek Group. Their work confirms the latest Precambrian age for the Walden Creek Group.

Southeast of the Greenbrier fault, the only stratigraphic unit known to overlie the Ocoee is the Murphy Belt Group (C_3), which McLaughlin and Hathaway (1973) report as containing Ordovician brachiopods and gastropods. The contact between the Ocoee and Murphy Belt Group was described as conformable by Power and Forest (1973) and as gradational by Mohr (1973).

Northeast of the Ocoee basins, volcanic rocks, largely subaerial, characterize the upper Precambrian stratified rocks on the west limb of the Blue Ridge anticlinorium. These volcanic rocks are assigned, from southwest to northeast, to: (1) the Grandfather Mountain Formation, exposed only in the Grandfather Mountain window (D_2), (2) the Mount Rogers Formation of southwestern Virginia (D_1), and (3) the Catoctin Formation north of Roanoke, Va. (D_3). The volcanic rocks, together with consanguineous intrusive rocks, constitute the bimodal Crossnore Plutonic-Volcanic Complex.[6] Metamorphosed basalt is ubiquitous, but rhyolite of peralkaline affinity is present in the Grandfather Mountain and predominates in the Mount Rogers and in the Catoctin Formation at South Mountain, Pa. Laminated pebbly mudstone and associated diamictite at the top of the Mount Rogers Formation and laminated pebbly mudstone near the highest exposed part of the Grandfather Mountain Formation may indicate an episode of late Precambrian glaciation. Zircons from five samples of rhyolite (Grandfather Mountain, Mount Rogers, and Catoctin Formations) give a discordia intercept age of *810* m.y. (Rankin and others, 1969).

The Grandfather Mountain Formation is structurally isolated from stratigraphically younger rocks, but the Mount Rogers and Catoctin Formations are overlain, with no obvious structural or metamorphic break, by clastic rocks of the Chilhowee Group. The contact between the Mount Rogers and Chilhowee is disconformable (Rankin, 1970). *Scolithus* is present locally in formations as low as the middle of the Chilhowee Group, and an *Ollenelus* fauna has been reported from a few localities at the top of the group.

Stratified rocks of definite latest Precambrian age are not found northeast of South Mountain, Pa., on the northwest flank of the Blue-Green-Long axis. Stratified rocks that crop out between the sparsely fossiliferous basal Lower Cambrian quartzitic sandstones and the older metamorphic complex are unnamed in the Reading Prong but are called the Dalton Formation (F) in Massachusetts and southern Vermont and the Pinnacle Formation (G) in central and northern Vermont. The Dalton and Pinnacle have traditionally been assigned an Early Cambrian(?) age, but they are not fossiliferous and may be totally, or in part, of late Precambrian age.

[6]This name was defined but informally designated "Crossnore plutonic-volcanic group" by Rankin and others (1973). The name Crossnore Plutonic-Volcanic Complex is herein adopted as a formal term.

EAST LIMB

No volcanic rocks on the east limb have been dated by the zircon U-Pb or whole-rock-isochron Rb-Sr methods, nor are Early Cambrian fossils known to exist in the area. A Precambrian age is suggested for the units shown on the chart on the basis of regional correlations. The supposition is strongest for northern Virginia and may be valid for northern and central Vermont. In both areas, stratified units of probable Precambrian age can be traced around the noses of anticlinoria exposing basement rocks. In northern Virginia, rocks of the Chilhowee Group overlie the upper Precambrian stratified rocks on the east limb of the Blue Ridge anticlinorium.

Stratified rocks of presumed late Precambrian age east of the Blue-Green-Long axis are thicker and contain a higher percentage of clastic sedimentary rocks, largely metamorphosed graywacke and shale, than do their counterparts west of the axis (Ocoee excepted), which contain a higher percentage of volcanic rocks.

A Precambrian age for the Lynchburg, Ashe, and Tallulah Falls Formations, the Great Smoky Group southeast of the Hayesville fault, and the Ashland, Wedowee, and Heard Groups presents some problems. These units contain numerous pods of ultramafic rock that range in size from a few meters to several kilometers. The ultramafic pods were emplaced prior to the major pulses of Ordovician(?) regional metamorphism, but their mode of emplacement is still debated. They are probably either fragments of obducted ophiolites emplaced in a sedimentary melange or along thrust faults or are diapiric.

Similar ultramafic pods along the east flank of the Blue-Green-Long axis in New England and near Washington, D.C., are interpreted as dismembered ophiolites obducted during the closing of the Iapetus Ocean and subsequently emplaced within the sedimentary pile (Rolfe Stanley, written commun., 1978; Drake and Morgan, 1981). In Vermont, the absence of pods in rocks younger than the Middle Ordovician Moretown Formation suggests that obduction had occurred by that time. Evidence from Newfoundland suggests that the obduction began in the Early Ordovician (Williams and Talkington, 1977).

Reasons for suggesting a Precambrian age for these strata on the east limb of the Blue Ridge anticlinorium include (1) the stratigraphic location of the Lynchburg Formation (J_2) beneath mafic rocks mapped as Catoctin and (2) the lithologic similarity of metamorphosed clastic rocks on both sides of the Hayesville-Fries fault (both called Great Smoky). A late Precambrian age is reasonable for the Fauquier and Catoctin Formations (J_3) of northern Virginia that lie stratigraphically beneath the Chilhowee on the east limb of the Blue Ridge anticlinorium. The Fauquier belt is on strike with the Lynchburg belt to the southwest, and the two are generally correlated. A thick greenstone overlies the Lynchburg east of Charlottesville and generally is assigned to the Catoctin. Alternatively, the Lynchburg may not be correlative with the Fauquier but, along with the Ashe, Heard, and Ashland, may be significantly younger, perhaps even as young as Ordovician. This age would be compatible with the origin of the Blue Ridge ultramafic pods as dismembered obducted ophiolites emplaced either as tectonic or as sedimentary melanges during the closing of the Iapetus Ocean. The younger age, however, would require the transportation of large volumes of clastic sediments across the carbonate bank lying west of the Blue Ridge.

INTRUSIVE ROCKS YOUNGER THAN 1 BILLION YEARS

Malfic and felsic dikes, sills, and plutons of the Crossnore Plutonic-Volcanic Complex, intrusive into the basement crystalline rocks and the Grandfather Mountain and Mount Rogers Formations, are particularly common near the Mount Rogers reentrant. Zircons from five granite plutons of the Crossnore have a discordia upper intercept age of *824* m.y., which is in good agreement with the *810*-m.y. U-Pb zircon age for comagmatic rhyolites (Rankin and others, 1969). Two of the samples used to determine the discordia curve for the granites are from earlier work by Davis and others (1962), and the other four are new analyses by T. W. Stern and M. F. Newell. In contrast, Odom and Fullagar (1971) reported a Rb-Sr whole-rock-isochron age of 672 m.y. for a composite isochron based on samples from the Beech, and Striped Rock Granites and the algirine-augite granite gneiss near Crossnore, N.C.

A peralkaline granite of Amissville in northern Virginia has a Pb-Pb zircon age of *655* m.y. with nearly concordant U-Pb ages (T. W. Stern, *in* Rankin, 1975). Lukert and others (1977) reported a U-Pb zircon age of 732 m.y. for the Robertson River Formation, and they interpret the Robertson River to be intrusive into the Virginia Blue Ridge Complex. These granites are presumably related to the late Precambrian breakup of eastern North America, although uncertainties remain as to the relation of these ages to the Crossnore plutons and to the rhyolite of the Catoctin Formation at South Mountain, Pa.

Bodies of foliated granite crop out near Kennesaw Ridge, Austell, and Hightower within the belt of the Ashland and Heard Groups in Georgia (H). This terrane lies northwest of the Brevard zone and along the east limb of the Blue-Green-Long axis. A tentative age of about 560 m.y. for these granitic gneisses is anomalous because nowhere else along the Blue-Green-Long axis do plutons of this age occur.

ALLOCHTHONS OF EASTERN ROCKS

INNER PIEDMONT AND SMITH RIVER ALLOCHTHONS

Between the Blue Ridge anticlinorium and structural domes to the east, which expose rocks older than 1 b.y., are terranes that are poorly understood in terms of tectonic setting, age of rocks, and geologic history. The largest of these, the Inner Piedmont (M_1), consists mostly of amphibolite-facies gneiss, schist, and amphibolite intruded by a variety of granitic rocks. Migmatite is characteristic of much of the terrane. Rankin (1975) suggested that the entire block is allochthonous and was transported from the southeast side of the Pine Mountain–Kings Mountain–Sauratown Mountains terrane. The new COCORP data, as interpreted by Cook and others (1979), also suggest that the Inner Piedmont is allochthonous.

Only two rock types from the Inner Piedmont have yielded isotopic ages of interest, although numerous granitic rocks have been dated as Paleozoic. The Henderson Gneiss (M_{1a}), a major unit of the western Inner Piedmont in North and South Carolina, is largely an augen gneiss of quartz monzonite composition. Most workers have interpreted the protolith of the Henderson to be metavolcanic (Bryant and Reed, 1970; Espenshade, *in* Rankin and others, 1973) or metaarkose (Hatcher, 1971). The Caesars Head Quartz Monzonite (Hadley and Nelson, 1971), a closely related and more massive rock, may be an intrusive rock. The Toluca Quartz Monzonite, the other dated rock, generally has been interpreted as an intrusive body.

The Rb-Sr whole-rock-isochron age of *524* m.y. for the Henderson agrees well with a zircon discordia intercept age of *526* m.y. on the same unit (Odom and Fullagar, 1973). A single zircon age for the Toluca by Davis and others (1962) falls essentially on the same discordia line and suggests a similar age (Odom and Fullagar, 1973). Hatcher (1971) considered the Henderson to be near the top of the stratigraphic section in the Inner Piedmont. The rocks of the Smith River allochthon are much like those of the Inner Piedmont and, presumably, at least overlap in age.

MARYLAND AND NORTHERN VIRGINIA PIEDMONT ALLOCHTHONS

Recent work by Crowley (1976), Drake and Morgan (1981), and Drake and others (1979) supports the interpretation that large masses of rock, including ultramafic-mafic complexes northwest of the Baltimore-Washington anticlinorium, were transported from southeast of the Baltimore Gneiss terrane. Detailed mapping by Drake and others (1979) in Fairfax County, Va., has delineated several lithotectonic units (N). Some rocks within these units may be of late Precambrian age, but solid evidence is lacking. This recent work supports the earlier suggestion by Rankin (1975) that parts of the Maryland and northern Virginia Piedmont are allochthonous, derived from southeast of the Baltimore Gneiss terrane, and perhaps are part of an eastern continent or continental fragment.

Higgins and others (1977) reviewed the problem of interpreting the existing isotopic ages for the Piedmont of the central Appalachians. From the data presented in their paper, we have selected the zircon ages from samples of rocks whose correlation is strongest—the metavolcanic rocks of the Chopawamsic and James Run Formations and the Baltimore paragneiss (Tilton and others, 1970; Higgins and others, 1977). The six zircon samples gave a recalculated discordia intercept age of *528* m.y. Between Washington, D.C., and Fredericksburg, Va., the Chopawamsic apparently is intruded by two plutons, the Occoquan Adamellite and the Dale City Quartz Monzonite, for which a discordia intercept age of *561* m.y. has been reported by Seiders and others (1975). Both the Chopawamsic and the Dale City Quartz Monzonite are unconformably overlain by the Ordovician Quantico Slate (Pavlides and others, 1980).

WESTERN GNEISS DOMES

Rocks older or probably older than 1 b.y. are exposed east of the Blue-Green-Long axis in the cores of a series of uplifts from Alabama (O_1) to Vermont (O_6). The old core rocks are interpreted as exposures of autochthonous or parautochthonous rocks of the North American craton (Naylor, 1975; Rankin, 1975), although Williams (1978) suggested that, south of latitude 36°, the old crystalline rocks may belong to the eastern continent.

Typically, the western gneiss domes consist of a crystalline complex of rocks older than 1 b.y., which is overlain nonconformably by a younger metasedimentary sequence. The mantling rocks commonly consist of quartzite, dolomitic marble, and schist. None of the metasedimentary units are fossiliferous, and none have been dated isotopically. The sequences, however, are very similar to the transgressive sequences of Cambrian and Ordovician age along the western flank of the Blue-Green-Long axis. Rankin (1975) suggested that the western gneiss domes may have originated as horsts on the eastern margin of a late Precambrian rift system.

PINE MOUNTAIN BELT

The Pine Mountain belt of Alabama and Georgia (O_1) is separated from the Inner Piedmont on the northwest by the northwest-dipping Towaliga fault and is separated on the southeast from the Uchee belt by the southeast-dipping Goat Rock fault. Rocks of the Pine Mountain belt consist of an older crystalline basement, predominantly orthogneiss, called the Wacoochee Complex and the younger metasedimentary Pine Mountain Group (Bentley and Neathery, 1970). Both the Wacoochee and the Pine Mountain are polydeformed and have undergone kyanite-grade Paleozoic metamorphism.

Within the Wacoochee Complex, the Woodland Gneiss of Hewett and Crickmay (1937) is probably equivalent to Clarke's (1952) Jeff Davis Granite. The predominant lithology is a biotite-garnet gneiss of quartz-monzonite composition; other rocks of the complex, such as the Cunningham Granite, are hypersthene bearing. A Rb-Sr-isochron age of *1051* m.y. has been obtained for the Woodland, and a zircon discordia intercept age of *1142* m.y. for the Cunningham.

KINGS MOUNTAIN BELT

The inclusion of the Kings Mountain belt (O_2), along strike to the northeast, in the group of western gneiss domes is problematical. No rocks demonstrably older than 1 b.y. have been identified, and the stratified rocks are distinctive because they include a significant volcanic component. Nonetheless, the position of the Kings Mountain belt along the Bouguer gravity gradient between the Inner Piedmont and the Charlotte belt and lithologic similarities argue that the belt forms a link between the Pine Mountain belt and the Sauratown Mountains anticlinorium.

SAURATOWN MOUNTAINS ANTICLINORIUM

Rocks in the core of the Sauratown Mountains anticlinorium (O_3) were interpreted by Espenshade and others (1975) to consist of an older suite of layered fine-grained biotite-quartz-plagioclase gneiss containing either muscovite or amphibole, biotite schist, and minor impure marble intruded by foliated granitic rocks (granite to diorite in composition) and augen gneiss. Espenshade and others (1975) included the plutonic rocks in the Elk Park Plutonic Suite. Foliated biotite-quartz monzonite near Pilot Mountain, N.C., has a zircon Pb-Pb age of *1,172* m.y. (T. W. Stern, *in* Rankin and others, 1973).

Distinctive foliated biotite-quartz monzonite, commonly containing fluorite, mesoperthite megacrysts, and, less commonly, dark-blue-green amphibole, is present also in the core of the Sauratown Mountains anticlinorium, as are foliated aegirine-bearing aplite dikes. These alkalic rocks are considered to be related to the late Precambrian rifting of the ancient North American craton. Zircons from two bodies of the alkalic rocks have been analyzed by Stern (Pb-Pb ages of *854* m.y. and *790* m.y.).

BALTIMORE GNEISS DOMES

Foliated granitic rocks, augen gneiss, layered gneiss, and minor amphibolite, collectively called Baltimore Gneiss (Crowley, 1976), crop out in the cores of a number of foliation folds (mostly domes) in the area of Baltimore, Md., and West Chester, Pa. (O_4). Pelitic rocks surrounding the domes have undergone Paleozoic metamorphism of sillimanite-muscovite grade.

The Baltimore Gneiss from several domes yielded ages in the range of 1–1.2 b.y. Samples of Baltimore Gneiss from the Phoenix, Towson, and Woodstock domes yielded a Rb-Sr whole-rock-isochron age of *1,028* ± *40* m.y. (Wetherill and others, 1968). Grauert (1974) published two precise discordia lines from the Baltimore area that suggest that the Baltimore Gneiss of the Towson dome is somewhat older (*1,180* ± *25* m.y.) than that of the Phoenix dome (*1,080* ± *20* m.y.). Grauert and others (1973) and Grauert (1974) showed that zircons from different facies of Baltimore Gneiss granulites from the West Chester Prong and the Avondale anticline yielded zircon discordia intercept ages of *980* and *1,060* m.y.

MANHATTAN PRONG

The basement complex of the Manhattan Prong (O_5) includes the Fordham Gneiss, Yonkers Gneiss, and Pound Ridge Granite Gneiss, all having undergone Paleozoic metamorphism of sillimanite grade. The Fordham is a heterogeneous unit consisting largely of gray biotite-quartz-feldspar gneiss; calc-silicate granulite and amphibolite are locally present (Hall, 1976). The Yonkers is a relatively homogeneous commonly pinkish biotite-ferrohastingsite-quartz-feldspar gneiss (Hall, 1976), and the Pound Ridge is a quartz-microcline-microperthite granite gneiss containing small amounts of biotite and muscovite (Mose and Hayes, 1975). The Yonkers and Pound Ridge occur as structurally concordant lenses within the Fordham. Hall (1976) interpreted the Fordham and Yonkers to be a metamorphosed eugeosynclinal sequence of sedimentary and volcanic rocks that contains some intrusive rock.

Zircons from the Fordham show a large spread in Pb-Pb ages, ranging from 800 to 1,300 m.y. (Grauert and Hall, 1973). They interpreted the data to indicate a 100- to 200-m.y. orogenic event, which ended about 980 m.y. ago. They also suggested that the zircon population contained a significant number of inherited zircons with "primary" ages of 1,600 to 1,700 m.y. Rb-Sr whole-rock-isochron ages ranging between 1,100 and 1,330 have been obtained for the Fordham Gneiss at three different localities (Mose and Hall, written commun., 1980). The Yonkers Gneiss and Pound Ridge Granite Gneiss, on the other hand, yielded much younger ages. Long (1969) determined a Rb-Sr whole-rock-isochron age of *563* ± *35* m.y. from the south end of the Yonkers outcrop area. Mose and Hall (written commun., 1980) obtained a Rb-Sr-isochron age of *528* ± 82 m.y. from the north end of the Yonkers outcrop area. Mose and Hayes (1975) determined a Rb-Sr whole-rock-isochron age for the Pound Ridge of *583* ± *25* m.y.

If the determined ages approximate the actual ages of the rocks and if the field relations have been interpreted correctly, an intrusive origin for the Yonkers and Pound Ridge is most likely. This extrusive or intrusive igneous event clearly is tied spatially to the western basement and may be related to the opening of the Iapetus Ocean.

CENTRAL BELT

The Central belt is, in many respects, a subdivision of convenience that has little continuity of geology along the orogen. The suture zone, representing the closing of the Iapetus Ocean, is interpreted to lie west of this belt, at least as far north as central Massachusetts.

CHARLOTTE BELT

The Charlotte belt (P) is characterized by an abundance of plutonic rocks including many mafic plutons that intrude stratified rocks of high metamorphic grade for which no systematic stratigraphy has yet been established. Tobisch and Glover (1971) concluded that, near the Virginia-North Carolina State line, the eastern edge of the Charlotte belt decreases sharply but continuously in metamorphic grade into the Carolina volcanic slate belt. Farther southwest, however, a fault separates the two belts.

The stratified rocks may be, in part, of Precambrian age, particularly if they are higher grade equivalents of the Carolina volcanic slate belt. Uranium-lead ages of the paragneiss are in the range *606-725* m.y. (Glover and others, 1971). Fullagar (1971) published Rb-Sr whole-rock data suggesting that some plutons may be as old as 500-600 m.y.

BRONSON HILL-BOUNDARY MOUNTAIN ANTICLINORIUM

Mantled gneiss domes that penetrate nappes derived from the east form a belt roughly parallel to and east of the Connecticut River extending from Long Island Sound north-northeastward to the Maine-New Hampshire boundary near Berlin, N.H. (Thompson and others, 1968). These domes constitute the Bronson Hill anticlinorium, which has been interpreted as a mobilized island-arc terrane. The oldest mantling strata are metamorphosed volcanic rocks, the Ammonoosuc Volcanics, of Middle Ordovician age. The core rocks consist of massive gneisses that may be intrusive and layered gneisses that may be metamorphosed sedimentary and volcanic rocks. Collectively, the core rocks are referred to as the Oliverian Plutonic Series and range in composition from quartz diorite to granite. Most of the core rocks that have been dated have Ordovician ages of about 450 m.y. (Naylor, 1975). Naylor and others (1973) reported a Pb-Pb age of *564* m.y., however, for the Dry Hill Gneiss of the Pelham dome, possibly an Oliverian dome on the west flank of the anticlinorium in Massachusetts (Q_1). This westernmost appearance of the eastern basement may indicate that the suture representing the closure of the Iapetus Ocean lies between the Pelham dome and the Athens and Chester domes (O_6).

The Boundary Mountains anticlinorium, an Acadian structure along the Maine-Quebec boundary, lies en echelon to the northwest of the Bronson Hill anticlinorium. An older complex, the Chain Lakes massif (Q_2), has been identified in the core of the anticlinorium. The stratigraphic succession that overlies the massif with probable unconformity is not agreed upon but contains rocks at least as old as Ordovician (Boudette and Boone, 1976). Interpretations differ also as to the protoliths of the massif, but some of the massif appears to be strongly retrograded and fragmented gneiss and migmatite. Naylor and others (1973) reported Pb-Pb ages of *1,476* and *1,486* m.y. for zircons from the massif. If these ages correctly date the Chain Lakes massif, that terrane would be the oldest identified in the Appalachians.

MERRIMACK SYNCLINORIUM

The Merrimack synclinorium of central New England consists largely of Silurian and Devonian rocks but locally exposes older rocks. High-grade gneisses and schists are exposed discontinuously along the southeastern margin of the synclinorium from north-central Massachusetts to south-central Maine. Besancon and others (1977) reported U-Pb ages for zircons from orthogneisses of the Massabesic Gneiss (R_1) near Manchester, N.H., in the range of 600-620 m.y. Aleinikoff and others (1979) suggested that the paragneiss of the Massabesic may be volcaniclastic in origin, with zircons yielding a minimum Pb-Pb age of *646* m.y.

The Cushing Formation of southwestern Maine (R_2) is lithologically similar to parts of the Massabesic Gneiss, as well as the Nashoba Formation of northeastern Massachusetts (U_2). The Cushing cannot be traced continuously into either unit but may be of early Paleozoic or late Precambrian age (Osberg, 1979). Farther northeast is the Passagassawakeag Gneiss in the vicinity of the Penobscot River, Maine (R_3), for which Stewart and Wones (1974) suggested a possible Precambrian age.

The Grand Pitch Formation of north-central Maine (R_4) consists of gray, green, and red slate and siltstone interlayered with vitreous quartzite and lesser amounts of graywacke and tuff (Neuman, 1967). The formation contains the trace fossil *Oldhamia* and is probably of late Precambrian or Early Cambrian age. It is overlain unconformably by rocks as old as Early or early Middle Ordovician.

AVALONIAN ZONE

Rocks of the Carolina volcanic slate belt and southeastern New England have much in common with rocks of the Avalon Peninsula of Newfoundland. We extend the name Avalonian zone into the Appalachians for these rocks, as did Williams (1978).

CAROLINA VOLCANIC SLATE BELT

Abundant mafic to felsic volcanic rocks, together with pelitic sedimentary rocks generally of low metamorphic grade, characterize the Carolina volcanic slate belt that extends from central Georgia to southern Virginia. Isotopic dating suggests that rocks toward the northern end of the belt may be older than those at the southern end.

The largest area of the Carolina volcanic slate belt for which detailed mapping reveals a consistent stratigraphy lies in central North Carolina between Albemarle and Asheboro (S_2) (Seiders and Wright, 1977). There, the metamorphic grade is low (chlorite and biotite zones), and the folds are broad and open. Volcanic and volcaniclastic rocks, overwhelmingly felsic, constitute most of the older part of the section (the Uwharrie Formation). The upper part of the section (the Albemarle Group) comprises mostly sedimentary rocks and lesser amounts of largely mafic volcanic rocks. The Millingport, the uppermost formation of the Albemarle, is the youngest unit preserved in this part of the Carolina volcanic slate belt. ?*Paradoxides carolinaensis* has been identified in a float piece of laminated argillite, probably from the Floyd Church Member, the lowest of two members of the Millingport (St. Jean, 1973).

Felsite near the top of the Uwharrie Formation has a U-Pb discordia intercept age of *584* m.y. (Wright and Seiders, 1981). Hills and Butler (1969) reported a Rb-Sr whole-rock-isochron age for rhyolite, also from the Uwharrie Formation, of *554* ±*50* m.y. An andesitic tuff that D. J. Milton (oral commun., 1980) places in the Floyd Church Member of the Millingport has an Rb-Sr whole-rock-isochron age of *540* ±*7* m.y. (Black, 1978).

R. H. Carpenter, A. L. Odom, and M. E. Hartley (written commun., 1978) described a generally similar stratigraphy along the Georgia-South Carolina boundary (S_1) about 260 km southwest of Albemarle. The basal Lincolnton Metadacite is overlain by a felsic pyroclastic sequence, which is, in turn, overlain by an upper sedimentary sequence, mainly banded argillite and thin interlayered mafic volcanic rocks. The workers suggested the correlation of the Lincolnton with the Uwharrie Formation and the correlation of the banded argillites of the upper sedimentary sequence with similar rocks of the Tillery Formation. They reported a Rb-Sr whole-rock-isochron age for the Lincolnton Metadacite of *547* ±*94* m.y., in reasonable agreement with a U-Pb zircon discordia intercept age of *566* ±*15* m.y., based on four zircon fractions of two of the same samples.

In the Roxboro-Durham area (S_3) along the eastern edge of the Charlotte belt, mafic and felsic gneisses of amphibolite facies (unit I of Glover and Sinha, 1973) are overlain with apparent conformity by unit II (Carolina volcanic slate belt) that consists mainly of felsic tuff and lapilli tuff with subordinate pyroclastic rocks and lavas of intermediate and mafic composition. Near Durham, N.C., rocks probably correlative with unit II contain impressions of worm-like forms, *Vermiforms antiquo* Cloud, n. gen., n. sp. (Cloud and others, 1976). Unit II is overlain by tuffaceous epiclastic rocks and reworked tuffs of unit III. The youngest stratified unit preserved, unit IV, consists of mostly mafic volcanic rocks to the north but felsic volcanic rocks to the south, all overlain by thin-bedded mudstone. This stratified sequence had been folded into a major syncline, and the synclinal axis offset more than 16 km along a left-lateral strike-slip fault (the Virgilina deformation) prior to the intrusion of the Roxboro Granite batholith.

Glover and others (1971) and Glover and Sinha (1973) reported that the gneisses of unit I may be as old as *725* m.y., based upon zircon analyses. Felsic tuff breccia near the top of map unit II has a U-Pb zircon discordia intercept age of *606* ±*20* m.y. (Glover and Sinha, 1973). High level plutons of the Flat River Complex (also called the Moriah pluton, Cloud and others, 1976) that may be intrusive equivalents of unit II have a zircon age of 650±30 m.y. (McConnell and others, 1976). Finally, the U-Pb discordia intercept age for the Roxboro Granite, based on two nearly coincident points (Glover and Sinha, 1973), is *564* m.y. These data imply that the stratified rocks of units I to IV were deformed after the extrusion of unit II *606* ±*20* m.y. ago but prior to the intrusion of the Roxboro Granite about *564* m.y. ago. This orogenic event has not been identified in the central and southern parts of the Carolina volcanic slate belt, from which stratified rocks, in general, yield younger ages. Wright and Seiders (1981) suggest that the Virgilina deformation was synchronous with the deposition of the upper part of the Albemarle Group but that the deformation did not extend into central North Carolina.

Rb-Sr whole-rock-isochron ages reported by Black and Fullagar (1976) for rocks near Chapel Hill are not easily related to the ages just discussed. They interpret the age of the Virgilina deformation to be 613 m.y. and theorize that plutons 638 and 705 m.y. old intrude dacite metatuffs (Efland Formation) that were affected by the Virgilina deformation.

SOUTHEASTERN NEW ENGLAND

Calc-alkaline plutonic rocks, such as the Dedham Granodiorite, are widespread in southeastern New England. At Hoppin Hill, near North Attleborough, Mass. (T_1), fossiliferous Lower Cambrian slates and limestones of the Hoppin Formation lie nonconformably upon coarse-grained igneous rocks similar to the Dedham Granodiorite. Billings (1929) suggested a Precambrian age for the Dedham Granodiorite on the basis of the relation at Hoppin Hill. Isotopic age studies now have established that an area bounded on the north and west by the Bloody Bluff, Lake Char, and Honey Hill fault zones contains large areas of upper Precambrian plutonic and volcanic rocks. This terrane had largely stabilized prior to deposition of Lower Cambrian sedimentary rocks and, thereafter, except for Alleghenian deformation, was involved only peripherally in Paleozoic penetrative deformation that strongly affected rocks immediately to the north and west. The southwestern part of this terrane, such as the Stony Creek dome near New Haven, Conn. (T_3), did undergo a considerable degree of Acadian metamorphism.

Included in the suite of upper Precambrian (600- to 650-m.y.-old) calc-alkaline plutonic rocks are the Stony Creek Granite of south-central Connecticut, the Scituate Granite of the Sterling Plutonic Group, the Esmond and Milford Granites and Ponaganset Gneiss of eastern

Connecticut and western Rhode Island (T_2), the granitic gneiss of the Willimantic dome, Connecticut (V), the Bulgarmarsh Granite of southeastern Rhode Island (W_2), and the Dedham Granodiorite and related rocks of eastern Massachusetts (U_1). R. E. Zartman and Naylor (unpublished data) have determined a Rb-Sr whole-rock-isochron age for the Milford Granite of *591 ± 50* m.y. and a U-Pb zircon discordia intercept age of *630 ± 15* m.y. for the Milford Granite and Dedham Granodiorite. Kovach and others (1977) determined a Rb-Sr whole-rock-isochron age of *595 ± 16* m.y. for the Dedham Granodiorite. Smith and Giletti (1978) reported a Rb-Sr whole-rock-isochron age of 603 ± 14 m.y. for the porphyritic granite of Aquidneck Island, R.I. (W_1). The Rb-Sr whole-rock-isochron age of *516 ± 13* m.y. determined by Galloway (Murray and Skehan, 1979) for the Bulgarmarsh Granite of southeastern Rhode Island may be reset partially by later metamorphism.

The calc-alkaline suite is intrusive into an older sequence of metasedimentary (quartzite, marble, schist, and gneiss) and metavolcanic rocks, the Blackstone Group and equivalents. The Plainfield Formation and Absalona Gneiss lying east of the Lake Char fault and south of the Honey Hill fault in Connecticut (T_2) and the Westboro Quartzite and Middlesex Fells Volcanic Complex in eastern Massachusetts (U_1) are probably roughly correlative with the Blackstone Group of Rhode Island (Quinn, 1971).

Sedimentary and volcanic rocks of the Boston basin (the Boston Bay Group) are younger than the Dedham Granodiorite that generally forms a basement for the basin. Until recently, the Boston Bay Group was considered to be of Carboniferous age. A study of the Mattapan Volcanic Complex beneath the Boston Bay Group has resulted in a precisely defined U-Pb-zircon discordia intercept age of *602 ± 3* m.y. (Kaye and Zartman, 1980). This age and new field observations suggest that deposition of the Boston basin sequence began in late Precambrian time and progressed more or less continuously into the Middle Cambrian (Braintree Argillite). Similar rocks in the smaller Woonsocket and North Scituate basins to the southwest also may be of Proterozoic age (Richard Goldsmith, oral commun., 1980).

In eastern Massachusetts, a fault-bounded terrane of poorly understood high-grade (sillimanite) metamorphic and plutonic rocks lies between the Avalonian zone on the southeast and the Merrimack synclinorium on the northwest (U_2) (Cameron and Naylor, 1976). The dominant stratified unit in this belt is the Nashoba Formation, composed mostly of felsic biotite gneiss, with lesser amounts of interlayered amphibolite, calc-silicates, and pelitic or quartzofeldspathic schists. Olszewski (1978) identified two zircon populations from this terrane. The first group consists of euhedral to subhedral cyrstals of presumed volcanic origin that give a U-Pb intercept age of about 750 m.y. The second group is made up of rounded and subrounded detrital zircons that have an upper discordia intercept age of about 1.55 b.y. The presence of volcanic zircons suggests that these strata formed during a late Precambrian episode of sedimentation and volcanism, whereas the presence of detrital zircon implies a significantly older source area for the terrigeneous metasedimentary rocks.

Terranes comparable to those of eastern Massachusetts may be present in south-central and coastal Maine. The Passagassawakeag Gneiss has already been noted in the section on the Merimack synclinorium. Stewart (1974) reported small areas of schist, quartzite, marble, and amphibolite intruded by pegmatite on Seven Hundred Acre Island and other small islands in Islesboro Township in Penobscot Bay, Maine (X). Brookins (1976) obtained a Rb-Sr whole-rock-isochron age of *734 ± 100* m.y. on samples of the metamorphic rocks and a Rb-Sr mineral-isochron age of *606 ± 20* m.y. on the pegmatite.

SOUTHEASTERN METAMORPHIC BELT

South of the Potomac River, a belt of medium- to high-grade metamorphic and plutonic rocks crops out adjacent to the Coastal Plain overlap. These rocks may be separated from the rest of the Piedmont to the northwest by the eastern Piedmont fault system of Hatcher and others (1977).

The southernmost segment in Georgia and adjacent Alabama is called the Uchee belt (Y_1). The dominant lithology, migmatitic granitic gneiss, was called the Phenix City Gneiss by Bentley and Neathery (1970). Four zircon samples from the Phenix City were analyzed by G. S. Russell and Odom (written commun., 1978), and the best-fit discordia line to the data yielded an upper intercept age of *566* m.y. However, such a line does not give a positive lower intercept, and it seems clear that not all the data form a single array. The Pb-Pb ages, most of which lie between *584* and *619* m.y., are probably a better estimate of the actual age than is the intercept of the chord with concordia.

The southeastern metamorphic belt in South Carolina is called the Kiokee belt (Y_2); it is characterized by amphibolite facies metasedimentary and metavolcanic rocks and stratiform granitic masses of orthogneiss. Secor and Snoke (1978) noted the similarity of the Kiokee and Carolina volcanic slate belts and suggested that they are, in part, correlative. The Kiokee belt is unusual in that it appears to have undergone amphibolite facies regional metamorphism in the late Paleozoic (Hercynian).

Rocks as high grade as kyanite crop out in the Raleigh belt (Y_3) east of the Deep River Triassic-Jurassic basin in North Carolina. According to Parker (1977), the Barrovian metamorphism is related to emplacement of the late Paleozoic (Hercynian) Rolesville batholith. Greenschist facies rocks south and east of the higher grade rocks are known as the eastern slate belt and correlate in general with the Carolina volcanic slate belt west of the Deep River basin. This terrane is, thus, much like the Kiokee belt and probably includes rocks of latest Precambrian age metamorphosed in late Paleozoic time. Parker (1977) implied that an older terrane also may exist in Wake County, N.C., where felsic quartzofeldspathic gneiss may lie unconformably beneath rocks correlated with the Carolina volcanic slate belt.

Pavlides (1976) reported a complexly folded terrane of schist, gneiss, and granite east of the outcrop belt of the Quantico Slate of Ordovician age. He referred to these rocks as the Fredericksburg Complex (Y_4); this complex corresponds, in part, with the area shown as Baltimore Gneiss by the Virginia Geological Survey (1928). He reported a Pb-Pb age of *594* m.y. for zircons from a hornblende-biotite paragneiss. Parts of the Fredericksburg Complex may be older. Glover and others (1978) reported a 1.0-b.y. age (Rb-Sr whole-rock-isochron) for a pluton near Richmond, Va., that intrudes rocks considered to be a southern extension of the Fredericksburg Complex (Louis Pavlides, oral commun., 1979).

MINERAL RESOURCES

The Adirondack province has been a fairly productive area of both metallic and nonmetallic minerals. Metallic deposits include the Tahawus-Sanford Lake magnetite-ilmenite deposit (Highlands), the largest titanium deposit in the United States; the Benson Mines magnetite-hematite deposit and similar but small deposits at Port Henry and Lyon Mountain (Highlands); syngenetic zinc deposits of Balmat-Edwards (Lowlands) that supply about 10 percent of the U.S. zinc production; and a number of small pyrite deposits in the Adirondack Lowlands. Nonmetallic deposits are also important in the Adirondacks. Graphite was produced from the Ticonderoga area of the Highlands. Each of the following mines is the largest producer of its kind in North America: the Barton Garnet mine of the Gore Mountain garnet deposit, which is a hydrous phase of an olivine metagabbro (Highlands); the Willsboro wollastonite deposit, a skarn deposit near Lake Champlain (Highlands); and talc-tremolite deposits in the complexly deformed carbonate-rich sequence of the Lowlands in the Balmat-Edwards district.

Rocks older than 1 b.y. in the Appalachians (the western basement) contain mineral deposits not unlike those of the Adirondacks. Historically, probably the most important are the unique zinc-manganese deposits in marble near Franklin, N.J. Other deposits in the western basement are relatively minor but include magnetite deposits in New York, New Jersey, and North Carolina, gold in North Carolina, and titanium associated with anorthosite near Roseland, Va. Nickel was produced from ultramafic rocks within the basement of the Mine Ridge anticline, Pennsylvania. Exploration for uranium is continuing in the billion-year-old basement terrane of the Grandfather Mountain window, North Carolina.

Mineral deposits in the stratified rocks of the Blue-Green-Long axis include minor native copper deposits in the greenstones of the Catoctin Formation, Va., and the massive sulfide deposit of the Great Smoky Group, Ducktown, Tenn., currently worked for sulfur, with copper as a byproduct. Similar deposits (Elk Knob, Ore Knob, Gossan Lead, Toncray) occur in the Ashe Formation of North Carolina and Virginia, although these host rocks may not be of Precambrian age. Other mineral occurrences in the stratified Precambrian(?) rocks on the east limb of the Blue-Green-Long axis include gold from the Dahlonega district, Georgia, mica pegmatite (of Paleozoic age) in Georgia, North Carolina, and Virginia, and minor precious and semiprecious stones (emerald, ruby, rhodelite), mostly in North Carolina.

Few mineral resources, other than stone, are known in Precambrian rocks between the Blue-Green-Long axis and the Avalon zone. Gold and relatively minor amounts of base metals were produced from the area of the Gold Hill fault zone, which is roughly the boundary between the Charlotte belt and the Carolina volcanic slate belt in southern North Carolina (S_2). Tungsten was produced from the Hamme district of the Virgilina area. Numerous pyrophyllite deposits occur in the Carolina volcanic slate belt.

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