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AGE OF PALEOZOIC REGIONAL METAMORPHISM IN THE CAROLINAS, GEORGIA, AND TENNESSEE SOUTHERN APPALACHIANS

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ABSTRACT. The zones of Paleozoic regional metamorphism have been broadly defined for most of the Southern Appalachians and can be correlated with available radiometric data. Major episodes of regional metamorphism occurred more than 430 m.y. ago in the Blue Ridge belt, about 410 to 430 m.y. ago in the Inner Piedmont belt, and about 380 to 420 m.y. ago in the belts farther southeast. Major metamorphism and deformation took place during the Taconic orogeny in the Blue Ridge belt and at least part of the region southeast of the Blue Ridge. Emplacement of the Spruce Pine swarm of pegmatite bodies in the Blue Ridge belt occurred about 380 m.y. ago. The widely quoted 250 and 350 m.y. "events" are not times of widespread metamorphic recrystallization in the exposed Southern Appalachians of the Carolinas, Georgia, and Tennessee. The timing of metamorphic events places a constraint on models for the evolution of this region.

INTRODUCTION

The time of the last major episode of regional metamorphism in the Southern Appalachians has been commonly assigned an age of about 350 m.y. (Long, Kulp, and Eckelmann, 1959; Kulp and Eckelmann, 1961; Bryant and Reed, 1970a). Carpenter (1970) concluded that metamorphic zones in the Blue Ridge of North Carolina formed during the period 320 to 375 m.y. Long, Kulp, and Eckelmann (1959), Kulp and Eckelmann (1961), and Hurst (1970) postulated a metamorphic event at about 250 m.y. in the Piedmont of the Southern Appalachians. In a summary paper on isotopic ages in the Appalachian region, Hadley (1964) pointed out some of the difficulties in interpreting the ages. Recent reviews of isotopic dating applied to geological problems emphasize the need to use several radiometric methods on a given problem and to make certain that the geological relationships of the samples are well known.

This paper reinterprets the Paleozoic metamorphic history of the Southern Appalachians, based on a review of published radiometric ages and an evaluation of their significance in the metamorphic evolution of the region. The geologic history of the samples dated is interpreted from published accounts and from recent work in several critical areas by the author. The conclusions reached here will be modified undoubtedly by future research.

Several papers have maps that broadly define the metamorphic zones in most of the Piedmont and Blue Ridge of North Carolina, South Carolina, Tennessee, and Georgia (Carpenter, 1970; Overstreet, 1970 and earlier papers; Smith, Wampler, and Green, 1969). The evidence reviewed in this paper strongly supports the conclusion that these metamorphic zones (that is, the main episode of Paleozoic regional metamorphism) formed before about 400 m.y. ago. There may have been even earlier Paleozoic metamorphism, but the evidence is inconclusive.

This paper supports the conclusion of Hadley (1964) that K–Ar and Rb–Sr mineral ages in this region record mainly crustal cooling by uplift and erosion. The 350 m.y. and 250 m.y. "events" should not be considered times of regional metamorphism and may not even be widespread synchronous events.

The terminology used here for the lithologic belts of the Southern Appalachians follows King (1955). The recently determined whole-rock Rb–Sr ages on many Piedmont intrusions (Fullagar, 1971) and interpretations of patterns of K–Ar mineral ages in other regional metamorphic terranes (Harper, 1967; Zartman and others, 1970) have greatly aided this study.

ISOTOPIC AGES AND REGIONAL METAMORPHISM

The Rb–Sr and K–Ar ages of minerals from metamorphic rocks are younger generally than the time of recrystallization (Yamaguchi and Yanagi, 1970, p. 382), and the deviation of the apparent mineral age from the true metamorphic age is greater in the higher metamorphic grades. Hart and others (1968) summarized the effects of contact metamorphism on isotopic ages, based on studies of minerals from the aureole of the Eldora stock in the Front Range, Colorado, and they suggested correlations with effects in zones of regional metamorphism. Biotite K–Ar and Rb–Sr ages are the most susceptible to resetting and should show effects of reheating even in the zeolite facies (200°-250°C). Hornblende K–Ar, zircon U–Pb, and feldspar Rb–Sr ages should show significant alteration of ages in the garnet-staurolite zone at about 500° to 550°C (Hart and others, 1968, p. 108). Zircon ^{207}Pb–^{206}Pb ages are the most resistant to resetting.

Some of the most valuable information on the effect of regional metamorphism on isotopic ages has come from the basement complexes of the Alps, where minerals formed during the Hercynian (Paleozoic) episodes of intrusion and regional metamorphism have been affected to differing degrees by the Alpine (Early Cenozoic) metamorphism. In the Alpine stilpnomelane zone, the transition from pre-Alpine to Alpine ages is observed for biotite Rb–Sr ages (Jäger, 1970, p. 164). According to Turner (1968, p. 303), stilpnomelane is generally restricted to the greenschist facies. Since biotite K–Ar ages are probably reset at slightly lower temperatures than biotite Rb–Sr ages, it would seem likely that temperatures of the biotite or garnet zone (greenschist facies) would be high enough to cause a general resetting of biotite K–Ar ages. In the zone of Alpine kyanite, no pre-Alpine biotite Rb–Sr ages are found, but coarse-grained muscovite may not be completely reset (Jäger, 1970, p. 166). Biotite in "basic rocks of high resistance to metamorphism" retained pre-Alpine ages, even though biotite in associated granitic rocks was completely reset to Alpine ages (Jäger, 1970, p. 165) in the chloritoid zone (upper greenschist or lower amphibolite facies).

Hart and others (1968, p. 106) emphasize that relative stabilities of mineral ages may change under different conditions and that no single detailed pattern of response of minerals to metamorphic conditions will be attained in all areas under all conditions. Nevertheless, it is clear that a very general pattern is emerging and that this pattern is useful in interpreting the history of orogenic belts (Armstrong, 1966).

One of the most reliable minimum ages for the time of regional metamorphism should be biotite K–Ar ages from progressively metamorphosed rocks in the biotite zone. Biotite and other potassium micas generally contain only negligible amounts of "excess" argon (Damon, 1968, p. 13-14) and, therefore, are unlikely to give anomalously old ages because of incorporation of extraneous Ar into the lattice. Temperatures in the biotite zone are less during regional metamorphism than in the higher metamorphic zones, which should allow the maximum chances of retaining true ages of regional metamorphism. In the following discussion, emphasis is placed on biotite and other mineral ages from metamorphic rocks of the lower-grade zones. Isotopic ages from ore zones and hydrothermally altered areas are omitted from the discussion because of the complex patterns that have been found in such areas (Fullagar and Bottino, 1970).

BLUE RIDGE

Recently published maps show the general configuration of metamorphic zones in the Blue Ridge province of North Carolina (Carpenter, 1970) and the entire crystalline Appalachian belt in Georgia (Smith, Wampler, and Green, 1969). Hadley and Goldsmith (1963, p. 97-107, pl. 3) present a map of metamorphic zones based on detailed studies in the Great Smoky Mountains of the western Blue Ridge province and discuss the evidence that the zones formed during the culmination of a major episode of Paleozoic metamorphism. These and other maps in limited areas allow the dated samples to be plotted on a map of metamorphic zones (fig. 1). Table 1 shows the available K–Ar dates from accurately known locations, grouped according to metamorphic zone.

Two of the dated biotites from the biotite zone (table 1) strongly support a minimum age of about 430 m.y. for the Paleozoic metamorphism. Biotite sample 3 (table 1) is from progressively metamorphosed rocks and is considered to be the most reliable indicator; samples 1 and 2 are from rocks of uncertain affinities. No dates have been reported on samples that are definitely from the garnet zone.

Dates from the staurolite zone (table 1) range from about 347 to 382 m.y. Three of the staurolite-zone samples are from progressively metamorphosed rocks. Sample 6 can be most accurately located; it is from the Thunderhead Sandstone of the Great Smoky Group at a locality about 1000 m southeast (on the high-rank side) of the staurolite isograd (Hadley and Goldsmith, 1963, pls. 1 and 3).

Samples from the kyanite zone (table 1) have dates generally equal to or lower than those of the staurolite zone, except for numbers 11 and 12 from metadolerite dikes. Detailed descriptions of the dike rocks (Wilcox and Poldervaart, 1958, p. 1338-1339) indicate that the biotite is metamorphic rather than igneous. Wilcox and Poldervaart (1958, p. 1361) conclude that these dikes were metamorphosed under water-deficient conditions. It is suggested here that the dates of about 433 ± 15 and 457 ± 21 m.y. are minimum ages for the Paleozoic metamorphism. Because of the water-deficient conditions in the dikes, very little argon diffused from the biotites after their formation. An alternate explanation is that the dates are anomalously old because of "excess" argon. Damon (1968, p. 16) and Armstrong (1966, p. 122) concluded that hypabyssal rocks contain excess argon more commonly than volcanic rocks, but the problem is less serious than in deep-seated intrusions.

Biotites from the sillimanite zone (table 1) have dates of less than 360 m.y., except for one that is about 438 m.y. Very little information is available on characteristics of the biotites or the nature of the host rock.

Fifteen K–Ar and Rb–Sr dates on biotites from the area between Roan Mountain and Hampton, Tenn. were reported by Long, Kulp, and Eckelmann (1959) and Davis, Tilton, and Wetherill (1962). The dates range from 892 to 380 m.y. Carpenter (1970, fig. 1) placed this area mainly in the garnet zone, but descriptions of rock samples in the earlier reports indicate extensive replacement of biotite by chlorite, particularly in the western part of the area. Carpenter's garnet could conceivably

Table 1

K–Ar ages of biotite and hornblende from metamorphic rocks northwest of the Brevard Zone, North Carolina, Tennessee, and Georgia

Sample number	Host Rock	Age	Reference
Biotite Zone			
1. F-4	Corbin Granite	430 ± 25	1
2. F-2	Fort Mtn. Gneiss	375 ± 20	1
3. L-133	Ocoee Series, Great Smoky Group	434 ± 15	2
Staurolite Zone			
4. L-132	Ocoee Series, Great Smoky Group	347 ± 13	2
5. K-11	Valleytown Fm., Cambrian(?)	373 ± 10	3
6. K-86	Ocoee Series, Great Smoky Group	382 ± 10	3
7. L-146	Cranberry Gneiss	357 ± 13	2
Kyanite Zone			
8. F-3*	Marblehill Hornblende Schist, Cambrian(?)	355 ± 20	1
9. K-84	"Carolina Gneiss"	359 ± 10	3
10. M-51	Banded gneiss	320	4
11. BK-149	Metadolerite dike, Precambrian	433 ± 15	2
12. BK-61	Metadolerite dike, Precambrian	457 ± 21	2
Sillimanite Zone			
13. K-23	"Carolina Gneiss"	307 ± 10	3
14. L-140	"Carolina Gneiss"	438 ± 14	2
15. K-78	"Carolina Gneiss'	344 ± 10	3
16. L-141	"Carolina Gneiss"	357 ± 13	2

References:
1. Smith, Wampler, and Green, 1969.
2. Long, Kulp, and Eckelmann, 1959.
3. Kulp and Eckelmann, 1961.
4. Davis, Tilton, and Wetherill, 1962.

* Number 8 is a hornblende sample; all others are biotite.

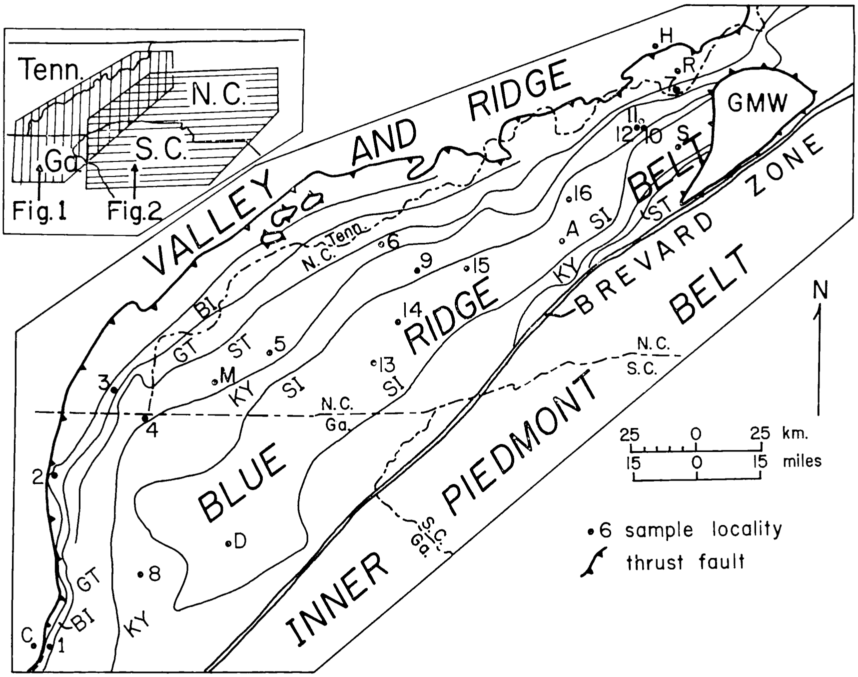

Fig. 1. Sketch map of western North Carolina, easternmost Tennessee, and northeastern Georgia, showing metamorphic zones and sample localities in the Blue Ridge belt. Zones: BI-biotite, GT-garnet, ST-staurolite, KY-kyanite, SI-sillimanite. Samples numbered according to table 1. Localities: GMW-Grandfather Mountain window, R-Roan Mtn., Tenn.; H-Hampton, Tenn., S-Spruce Pine, N.C.; A-Asheville, N.C.; M-Murphy, N.C.; D-Dahlonega, Ga.; C-Cartersville, Ga. Modified after Carpenter, 1970; Smith, Wampler, and Green, 1969, and references cited in the text.

have come from the older Precambrian basement gneisses exposed over much of the area. The easternmost samples of this group are from near Roan Mountain, Tenn., and have ages of 420 to 380 m.y. (Davis, Tilton, and Wetherill, 1962, p. 1991) and 439 ± 17 to 418 ± 16 m.y. (Long, Kulp, and Eckelmann, 1959, p. 587, 594). These dates must be interpreted cautiously until the isograds are located more accurately, but the data lend some support to the conclusions of this paper.

Pegmatite bodies and associated granitic intrusions in the Blue Ridge region of North Carolina are almost exclusively located in the kyanite and sillimanite zones (Carpenter, 1970, p. 758). The pegmatites were probably intruded during Paleozoic regional metamorphism (Lesure, 1968, p. 15). The numerous dates on pegmatite minerals from the Spruce Pine area (tabulated by Lesure, 1968, table 1) are mainly discordant U–Pb dates, or Rb–Sr and K–Ar dates mainly less than 350 m.y. As pointed out by Hadley and Goldsmith (1963, p. 107), probably the most reliable dates for the pegmatite bodies are the concordant dates (table 2, no. 17) reported by Aldrich and others (1958, p. 1128). The

TABLE 2

Selected mineral ages from pegmatites of the Blue Ridge and granitic rocks of the Inner Piedmont

Number	Location	Mineral	K–Ar	Rb–Sr	Dates (m.y.) ^{238}U–^{206}Pb	^{235}U–^{207}Pb	^{207}Pb–^{206}Pb
17.	Chestnut Flat mine,	Uraninite			385	390	400 ± 50
	Spruce Pine, N.C.	Uraninite			370	375	420 ± 50
		Muscovite	335	375			
		K-feldspar		385			
18.	Iotla mine, near	Muscovite		512 ± 28			
	Franklin, N.C.	Biotite		293 ± 15			
19.	Grindstaff mine,	Muscovite		508 ± 15			
	near Franklin, N.C.	Biotite		256 ± 14			
20.	Elberton granite, Elberton, Ga.	Zircon			450	455	465
21.	Saprolite from Elberton granite	Zircon			490	480	415
22.	Toluca quartz monzonite,	Zircon			405	415	480 ± 50
	Toluca, N.C.	Biotite		250			
23.	Cherryville quartz monzonite,	Biotite		375			
	Shelby, N.C.	Muscovite		350			

References: 17, Aldrich and others, 1958; 18-19, Deuser and Herzog, 1962; 20-21, Grunenfelder and Silver, 1958; 22-23, Davis, Tilton, and Wetherill, 1962.

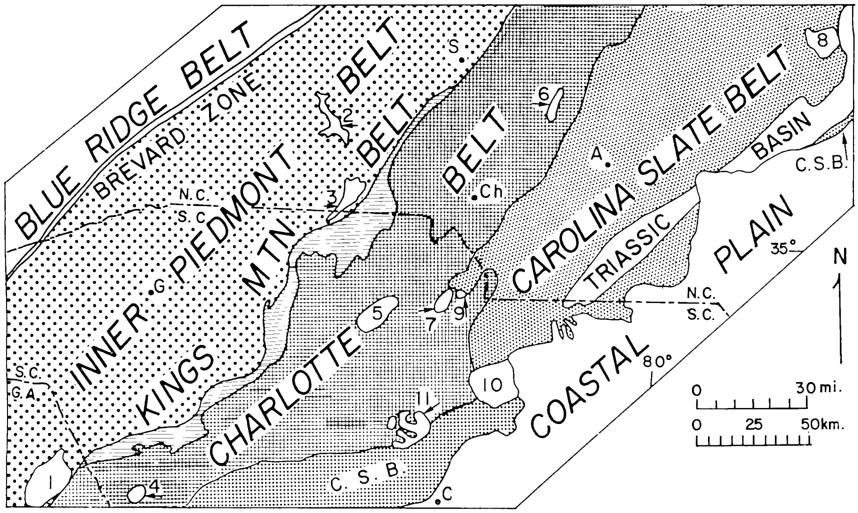

Fig. 2. Sketch map of parts of the Piedmont in North Carolina, South Carolina, and Georgia, showing the location of selected intrusions. Names of intrusions: 1-Elberton, 2-Toluca, 3-Cherryville, 4-Mt. Carmel, 5-Lowrys, 6-Salisbury, 7-Edgmoor, 8-Farrington, 9-Catawba, 10-Liberty Hill, 11-Winnsboro. Abbreviations: CSB-Carolina slate belt, A-Albemarle, C-Columbia, G-Greenville, S-Statesville. Modified after Butler and Ragland, 1969, and references cited in text.

dates indicate an age of about 380 m.y. for the Spruce Pine swarm of pegmatites. Dates of about 510 m.y. (table 2, nos. 18, 19) on muscovite from pegmatites near Franklin, N.C. (Deuser and Herzog, 1962, p. 1999), may possibly indicate an earlier episode of pegmatite intrusion, but the data are too few to be conclusive.

INNER PIEDMONT

The geology of the Inner Piedmont is poorly known, and there are relatively few isotopic dates from the rocks. The dates from the Stone Mountain pluton, Lithonia Gneiss, and related units near Atlanta, Ga. (Smith, Wampler, and Green, 1969) are inconclusive with respect to the time of regional metamorphism. The mica ages range from 280 to 340 m.y. and would be expected to give dates younger than the culmination of metamorphism, since they are all from the kyanite and sillimanite zones. The Elberton batholith (fig. 2) is emplaced in the sillimanite zone (Smith, Wampler, and Green, 1969, pl. 1) and is late- or post-tectonic (Ramspott, 1964). It was emplaced apparently after the major episode of regional metamorphism but shows deformation related either to late stages of emplacement or to a later episode of dynamic metamorphism (Ramspott, 1964, p. 228-229). Of two zircon samples from the Elberton granite (table 2, nos. 20 and 21), the more concordant one indicates an age of about 455 m.y. The mica dates range from 245 to 345 m.y. (Pinson and others, 1957; Long, Kulp, and Eckelmann, 1959). These data are also inconclusive but indicate that the sillimanite-zone metamorphism occurred more than 450 m.y. ago.

The only dates from the Inner Piedmont of North Carolina pertinent to this discussion are from the Toluca and Cherryville quartz monzonites. The Toluca quartz monzonite occurs in numerous generally concordant bodies that have gneissic structure and commonly contain garnet (Griffitts and Overstreet, 1952). The Toluca bodies were emplaced before or during strong regional metamorphism (Overstreet and Bell, 1965, p. 67). The Cherryville quartz monzonite is found in cross-cutting plutons and is generally massive in texture and structure. The Cherryville plutons are clearly younger than the last major episode of deformation and are most likely younger than the regional metamorphism. The Toluca plutons are in the sillimanite zone and the Cherryville plutons in the sillimanite, kyanite, and staurolite zones (Overstreet and Griffitts, 1955; Overstreet and Bell, 1965). The uranium-lead dates on zircons (table 2, no. 22) suggest an age of at least 410 to 430 m.y. for the Toluca quartz monzonite. Fullagar (1971, p. 2856) states that the Cherryville quartz monzonite has an age of about 400 m.y., based on six whole-rock Rb–Sr determinations. Biotite from the Cherryville (table 2, no. 23) indicates a minimum age of 375 m.y. These dates indicate that high-rank regional metamorphism occurred in this region at least 430 to 410 m.y. ago and that the peak of metamorphism had passed before about 400 to 375 m.y. ago.

CHARLOTTE BELT

Fullagar (1971) presented whole-rock Rb–Sr isochron ages for 14 plutons, mainly in the Charlotte belt and Carolina slate belt of North Carolina and South Carolina. He concluded that the thermal peak of the last significant metamorphic event occurred 380 to 420 m.y. ago.

Medlin (ms, p. 182-183) reported K–Ar dates of 380, 386, and 387 m.y. for biotites of the post-metamorphic Mt. Carmel complex, South Carolina. The Lowrys granitic pluton, South Carolina, which has a whole-rock isochron age of 407 ± 11 (Fullagar, 1971), shows no effects of regional metamorphism or deformation (Butler and Ragland, 1969). The Salisbury albite adamellite intrusion has a whole-rock isochron age of 411 ± 6 m.y. and was probably emplaced before or during regional metamorphism (Fullagar, Lemmon, and Ragland, 1971).

The Edgmoor pluton was classified as post-metamorphic (Butler and Ragland, 1969) but was later found to have an isochron age of 545 ± 30 m.y. (Fullagar, 1971). The classification was based on scanty evidence because of very poor exposures and is probably incorrect. Metamorphic rocks in the area around the pluton are in the amphibolite facies (Butler, 1966), and metamorphism in this facies may not have caused noticeable mineralogical and textural changes unless accompanied by strong deformation. The Great Falls pluton, which is clearly premetamorphic, has an isochron age of 554 ± 63 m.y.

The dates from the Charlotte belt indicate that regional metamorphism ended more than 380 to 400 m.y. ago in at least two parts of the belt in South Carolina. It may have ended about 410 m.y. ago in parts of North Carolina.

CAROLINA SLATE BELT

Several lines of evidence give an older bracket on the time of metamorphism in the slate belt of central North Carolina. Trilobite specimens of Early or Middle Cambrian age occur in meta-argillite (St. Jean, 1965), and the youngest dated meta-rhyolite has a whole-rock Rb–Sr isochron age of 520 ±15 (Hills and Butler, 1969). The regionally metamorphosed Farrington complex (Butler and Ragland, 1969) has a whole-rock isochron age of 519 ± 125 m.y. (Fullagar, 1971). These dates indicate that the metamorphism in the slate belt is Paleozoic, probably younger than Cambrian.

Fullagar (1971) gives isochron ages for three granitic intrusions in South Carolina located along the Charlotte belt-Carolina slate belt boundary: (1) Catawba, 325 ± 50 m.y., (2) Liberty Hill, 299 ± 48 m.y., and (3) Winnsboro, 301 ± 10 m.y. The first two are clearly post-metamorphic and post-tectonic, as they cut schistose rocks of the greenschist facies along parts of their contacts, but are unfoliated and relatively unaltered (Butler, 1965; Butler and Ragland, 1969). The Winnsboro complex is emplaced in greenschist-facies rocks in the southeastern part and in sillimanite-grade rocks in the northwestern part (Wagener, 1970). Wagener considered that part of the complex was syn-metamorphic and part was post-metamorphic. The position of the complex straddling the major metamorphic gradient is here considered evidence that the complex is younger than the main episode of regional metamorphism.

Regional metamorphism in the Carolina slate belt can be bracketed only between the dates of about 520 and about 300 m.y. ago.

CONCLUSIONS

The following conclusions are drawn with respect to dating of the Paleozoic regional metamorphism in North Carolina, South Carolina, Georgia, and Tennessee:

1. The peak of regional metamorphism was attained in the Blue Ridge province at least 430 m.y. ago. It is unlikely that the biotites retained all radiogenic argon from the time of metamorphic crystallization, so the 430 m.y. age may be a minimum. The regional metamorphism may well have occurred during the Taconic orogenic episode (450-500 m.y. age, according to Rodgers, 1970, p. 216). The 430 m.y. dates show up in biotite, kyanite, and sillimanite zones, so probably all these zones were formed during the same metamorphic cycle. The pegmatite bodies of the Spruce Pine area were formed about 380 m.y. ago, which conforms to the time of the Acadian orogeny (360-400 m.y. according to Rodgers, 1970, p. 216; about 380 m.y. according to Naylor, 1971). Since the pegmatite bodies are almost exclusively confined to the kyanite and sillimanite zones (Carpenter, 1970, p. 758), pegmatite formation may be genetically related to regional metamorphism. Did the high-grade metamorphic conditions continue unabated from before 430 m.y. until after 380 m.y. or were there two separate episodes of metamorphism? I favor the interpretation of two separate episodes, one Taconic and one

Acadian. If the conditions had remained intense for more than 50 m.y., it seems likely that all the micas would have been reset to younger dates. Probably the Acadian episode involved reheating that followed the general pattern of the earlier episode but did not greatly disturb the position of the isograds. This reheating caused some resetting of mica dates and was accompanied by pegmatite intrusion.

The radiometric ages do not afford an older bracket on the age of the > 430 m.y. metamorphism; however, stratigraphic evidence supports the conclusion that rocks of the Blue Ridge were not subjected to deformation or metamorphism during Cambrian or Early Ordovician time (Bryant and Reed, 1970b, p. 174). The maximum age of the > 430 m.y. metamorphism may therefore be about 470 m.y.

2. The present scanty data for the Inner Piedmont indicate a tentative age of about 410 to 430 m.y. for the peak of metamorphism in North Carolina but perhaps an age of more than 450 m.y. in the Elberton area of Georgia. The latter age is not very firmly established, and it is one of the few indications of Taconic(?) metamorphism southeast of the Blue Ridge belt. The culmination of regional metamorphism in the Charlotte belt probably occurred about 380 to 420 m.y. ago (Fullagar, 1971). The difference in the apparent ages for the Inner Piedmont and Charlotte belts may or may not be significant. The tentative conclusion here is that regional metamorphism occurred at least in some places in the Inner Piedmont during the Taconic episode but reached highest-grade conditions in parts of North Carolina during the Silurian. Metamorphism in the Charlotte belt may have reached a peak in Late Silurian or Early Devonian, which would make the episode somewhat older than typical Acadian episodes farther north.

3. In a general way, there may be a progressive decrease in age of the peak of metamorphism southeastward across the Southern Appalachians, from as old as Taconic in the Blue Ridge to nearly as young as Acadian in the Charlotte belt.

4. Regional metamorphism in the Carolina slate belt can be bracketed between the ages of 520 and 300 m.y. At several localities in North Carolina and South Carolina, there appears to be a continuous or nearly continuous metamorphic gradient from the slate belt into the Charlotte belt to the west; this implies, but does not prove, that metamorphism occurred at about the same time in both belts. If the apparent progressive southeastward decrease in age of the peak of metamorphism can be extended to the slate belt, then metamorphism in the slate belt may be Acadian; however, this is only speculation at the present time.

5. The K–Ar and Rb–Sr mineral dates range from 310 to 890 m.y. in the Blue Ridge belt, from 235 to 375 m.y. in the Inner Piedmont, and from 226 to 352 m.y. in the belts southeast of the Inner Piedmont. This review and Fullagar's (1971) results reinforce Hadley's (1964) conclusion that the mineral dates record mainly crustal cooling by uplift and erosion rather than times of metamorphic or igneous crystallization. The widely quoted date of 350 m.y. for Paleozoic metamorphism is not a

time of extensive metamorphic recrystallization. A histogram of mineral dates from the Southern Appalachians (Hadley, 1964, fig. 4) has the most prominent peak at about 350 m.y. This peak is partly due to sampling bias, as most of the 350 m.y. dates are from the Blue Ridge belt. The 350 m.y. dates in the Blue Ridge probably represent fixation of dates due to cooling after the episode of heating and pegmatite intrusion at 380 m.y.

6. Three unmetamorphosed plutons (Catawba, Liberty Hill, and Winnsboro) with ages of about 300 m.y. and one (Lowrys) with an age of about 400 m.y. (Fullagar, 1971) lie in the "250 m.y. axis" of Kulp and Eckelmann (1961). The axis in the Carolinas and Georgia is defined mainly by 11 mineral dates of about 250 m.y. (Kulp and Eckelmann, 1961, fig. 1; Hurst, 1970, fig. 5), mostly from units of poorly known age and origin. On the basis of present evidence, it is considered unlikely that the 250 m.y. "event" is a time of widespread metamorphic recrystallization.

DISCUSSION

It is important to consider the timing of regional metamorphism in relation to episodes of deformation; however, a detailed review of the evidence is beyond the scope of this paper. Hadley and Goldsmith (1963, p. 106) found that an episode of folding and thrusting preceded the peak of metamorphism in the Great Smoky Mountains of the Blue Ridge belt. They (table 16) concluded that this early deformation was probably Ordovician and the main regional metamorphism Middle or Late Devonian. The conclusion of this paper is that the metamorphism was also probably Ordovician.

In the Brevard zone and Inner Piedmont belt of North Carolina, a very intense episode of folding either accompanied or preceded the main metamorphic episode (Overstreet and Griffitts, 1955; Butler and Dunn, 1968; Stirewalt, ms). This folding is probably not Acadian; it may have occurred during the Taconic orogeny or perhaps somewhat later (Silurian or Early Devonian?) than the usual range of the Taconic. In part of the Carolina slate belt and Charlotte belt in North Carolina, major folding and nappe formation preceded the peak of regional metamorphism (Tobisch and Glover, 1971, fig. 20), but the folding may have occurred during the late Precambrian or earliest Paleozoic (Glover and others, 1971).

A post-metamorphic episode of deformation, which mainly produced open folds and slip cleavage, has been recognized in the Blue Ridge belt (Hadley and Goldsmith, 1963), Inner Piedmont belt (Butler and Dunn, 1968; Stirewalt, ms), and Charlotte belt-Carolina slate belt (Tobisch and Glover, 1971). This late episode may range in age from place to place, and there is little direct evidence of the age southeast of the Blue Ridge belt. The Blue Ridge thrust sheet was emplaced sometime during the Late Paleozoic (Late Mississippian to Permian; Bryant and Reed, 1970b, p. 176-178), and a widespread post-metamorphic episode of deformation may have accompanied the thrusting. The 300 m.y. plutons dated by Fullagar (1971) show no evidence of deformation, which may indicate that Late Paleozoic deformation did not extend into the eastern Charlotte belt and adjacent Carolina slate belt.

Retrogressive metamorphism is sporadic but widespread in the Southern Appalachians, and it is particularly intensive in the Brevard zone. The retrogression has not been definitely dated and may range widely in age. It does not affect the 300 m.y.-old plutons studied so far.

The Late Paleozoic deformation (Alleghanian orogenic episode) apparently was not accompanied by intrusion of any major series of plutons or by formation of a consistent pattern of metamorphic zones in any part of the exposed Appalachians in North Carolina, South Carolina, Georgia, or Tennessee. Some of the post-metamorphic gabbro–diorite–syenite intrusions (Butler and Ragland, 1969) could be of Late Paleozoic age, but preliminary data (Fullagar, 1971) make it doubtful. Further work could modify this conclusion, even though at least some parts of all the major belts have been studied.

As in the Blue Ridge belt and at least some other parts of the crystalline Southern Appalachians, the Taconic orogenic episode apparently had major effects in the Central Appalachians. Dates on rocks and minerals from the Maryland Piedmont obtained by a variety of methods indicate that major plutonism, deformation, and metamorphism had been completed by about 425 m.y. ago (Wetherill and others, 1966, p. 2146). On the other hand, times of Paleozoic regional metamorphism in the exposed parts of the Southern and Central Appalachians may be quite different from the times in the Northern Appalachians. Thompson and Norton (1968, p. 325) state that evidence supports major regional metamorphic episodes in the Northern Appalachians in mid-Devonian (Acadian) and Pennsylvanian or Permian (Alleghanian), with a possibility of a pre-Silurian episode in northern Vermont and southern Quebec. The general pattern of oldest Paleozoic metamorphism near the northwestern part of the belt and youngest in the southern and southeastern part is at least the same sequence although generally not the same ages as postulated in this paper for the Southern Appalachians.

In the Piedmont of the Southern Appalachians, the K–Ar dates on minerals from syn- or pre-metamorphic rocks are commonly 100 to 150 m.y. younger than the time of major metamorphism. Similar situations have been noted in other regional metamorphic terranes. In the Northern Appalachians of New England, Zartman and others (1970) outlined a region of Permian disturbance (200-260 m.y.) of K–Ar dates on minerals from rocks that were known in many cases to be older than 350 m.y. Many of the mica dates are therefore more than 100 m.y. younger than the time of metamorphism. The disturbed belt in New England coincides approximately with the sillimanite zone of regional metamorphism (mainly Acadian metamorphism). In the Scottish Caledonides, mineral and whole-rock K–Ar dates on metamorphic rocks are commonly at least 50 to 70 m.y. younger than the peak of regional metamorphism (Harper, 1967). In Japan, Rb–Sr and K–Ar mineral ages are in many cases 40 to 60 m.y. younger than the main metamorphic event (Yamaguchi and Yanagi, 1970). These studies in the Northern Appalachians, Scottish Caledonides, and Japan all support a basic premise of this paper, that K–Ar and Rb–Sr mineral dates from the lower-rank zones of metamorphism are generally closer to the time of culmination of metamorphism than dates from the higher-rank zones. Whole-rock K–Ar dates on phyllites from low-rank zones may give even better dates for the metamorphism (Harper, 1967), but none from the Southern Appalachians have been published yet.

The timing of regional metamorphism places a constraint on models for the evolution of the Southern Appalachians. For example, Griffin (1970) proposed extensive deformation and northwestward thrusting related to rise of a mobile core in the Inner Piedmont caused by underthrusting of a continental plate by an oceanic plate. Griffin did not discuss the ages of these events. Rise of a mobile core should be associated with widespread medium-to-high-rank regional metamorphism and with emplacement of granitic plutons. The evidence in the exposed Southern Appalachians is against the development of a mobile core and associated features during the Alleghanian orogeny. The Late Paleozoic thrusting in the Southern Appalachians may have taken place 50 m.y. after the last major intrusive igneous episode and possibly more than 100 m.y. after the last major regional metamorphic episode. Viable models for the evolution of the Southern Appalachian segment discussed here should account for the timing of these events.

This study supports the conclusions of Rodgers (1970, p. 202; 1971, p. 1169) that deformation and metamorphism correlative or approximately correlative with the Taconic orogeny farther north were extremely important in the evolution of the Southern Appalachians. The importance of the 250 and 350 m.y. "events" with regard to deformation, metamorphism, and igneous intrusion in the Southern Appalachian Piedmont has been greatly overplayed in recent papers, including my own (Butler, 1966, p. 14).

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