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METAMORPHIC MAP OF THE APPALACHIANS

By

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MISCELLANEOUS GEOLOGIC INVESTIGATIONS
MAP I-724

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MORGAN—METAMORPHIC APPALACHIANS 1:2,500,000 MAP I-724

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INTRODUCTION

This map depicts the major metamorphic belts of the Appalachian mountain system within the United States. Degree of metamorphism is expressed in terms of isograds, mineral facies, and mineral facies series.

The isograds on the accompanying map are defined by the first prograde appearance of an index mineral without regard to a specific chemical reaction and without rigor as to the chemical composition of the index mineral or chemistry of the total system. Wherever possible, isograds are shown in rocks of approximately similar total composition. A more rigorous definition and use of an isograd was not practicable, owing to the necessity of compiling information from a wide variety of reports and broad extrapolation in many areas. The isograds used for rocks of pelitic composition are biotite, garnet, andalusite, kyanite, sillimanite, and sillimanite-orthoclase. The complete set of isograds is used only in New England and New York; insufficient information for the occurrence of biotite and kyanite prevented depiction of these isograds throughout the southeastern Appalachians.

Mineral facies and mineral facies series, as used here, are defined on the basis of the isograd data and are at some variance with definitions proposed by several writers (Fyfe and Turner, 1966; Winkler, 1967). The facies of metamorphism are mineral facies based on key minerals from pelitic rocks rather than ensembles of mineral assemblages from specific localities (Thompson, 1957). The granulite facies is defined by the assemblage quartz-sillimanite-orthoclase in rocks of pelitic composition. The epidote-amphibolite and almandine amphibolite facies have been combined as the amphibolite facies and are delimited by the garnet and sillimanite-orthoclase isograds. The greenschist facies includes all masses of rock of pelitic composition that do not contain garnet.

The lower limit of greenschist metamorphism and the boundary between metamorphism and diagenesis are not defined. This poses no problems in map compilation along the entire eastern and southern margins of the Appalachians where the greenschist and amphibolite facies rocks are unconformably overlain by unmetamorphosed rocks of the Atlantic and Gulf Coastal Plain. In areas where a continuous gradation between greenschist and unmetamorphosed rocks exists, a subgreenschist or transitional facies of metamorphism has been recognized. The two principal areas designated as subgreenschist facies are northern Maine and Cambrian-Ordovician units within the Great Valley and the eastern part of the Ridge and Valley provinces in the central and southern Appalachians. The subgreenschist facies in northern Maine is the area designated as a subchlorite zone by Hussey and others (1967). Coombs, Horodyski, and Naylor (1970) have reported the occurrence of a prehnite-pumpellyite facies within a part of this area. Formations within the Great Valley and the Valley and Ridge provinces may or may not be regarded as metamorphosed (see for example Ray and Gault, 1961; Maxwell, 1962; Drake, 1969) depending on the definitions used. Although A. A. Drake, Jr. (oral commun., 1970) has evidence that much of the Martinsburg Formation in the Great Valley province of eastern Pennsylvania is metamorphosed to the greenschist facies, the western boundary of the subgreenschist facies is arbitrarily taken as the western contact of the Martinsburg Formation within eastern Pennsylvania and the western boundary of Cambrian-Ordovician rocks east of the Pulaski fault in Virginia and Tennessee and southeast of the Rome fault in Georgia. The occurrence of pumpellyite at Bunker Hills, Pa. (Zen, 1971), and prehnite in the greenstones of the Catoctin Formation near Luray, Va. (W. G. Melson, oral commun., 1969), indicates a possibility of a widespread prehnite-pumpellyite metamorphic facies within these rocks heretofore undetected because of the limited number of investigations and the limited occurrence of rocks of the prerequisite chemical composition.

Laumontite-quartz-albite assemblages have been described in arkoses in the Connecticut Triassic basin (Heald, 1956). These rocks may be in a zeolite facies, but this metamorphism is clearly post-Paleozoic and not related to other metamorphic episodes shown on the map. The laumontite-quartz-albite assemblages are not transitional into areas of prehnite-pumpellyite or greenschist metamorphic facies. These rocks are indicated on the map by the letter z.

Two facies series have been recognized in the Appalachians: a low pressure/temperature (P/T) facies series in the northern part of New England and an intermediate P/T facies series in the remainder of the Appalachians. These facies series are defined by the polymorphic transitions of andalusite to sillimanite and kyanite to sillimanite, respectively. There are no occurrences of glaucophane, metamorphic aragonite, jadeite, or lawsonite in the eastern United States to define a high P/T facies series.

PRECAMBRIAN METAMORPHIC BELTS

The areas shown in shades of brown represent the oldest rocks known in the Appalachians. The Adirondack massif was metamorphosed during the Precambrian but not by subsequent Paleozoic metamorphic events. The Adirondack massif, flanked by unmetamorphosed Paleozoic rocks, is a part of the Precambrian basement of Grenville age that may underlie the unmetamorphosed fold belt along the west flank of the Appalachian mountain system. In the area of the Adirondack massif, this basement has not been extensively modified by Paleozoic metamorphism except for cataclastic shearing and local retrogression along the eastern and southeastern margins. The greater part of the Adirondacks is considered to be in the granulite facies (Buddington, 1963; Waard, 1965) defined by an orthopyroxene-clinopyroxene-hornblende isograd (h) in rocks of basaltic composition and the widespread occurrence of the assemblage quartz-sillimanite-orthoclase in rocks of appropriate composition. In the northwestern Adirondacks, the regional metamorphism is in the amphibolite facies; sillimanite is abundant, cordierite is present, kyanite is absent. The progressive metamorphism from amphibolite to granulite facies described by Engel and Engel (1958, 1960) is probably typical of a low P/T facies series.

The darker brown areas represent the Precambrian infrastructure within the Appalachian system. These areas are polymetamorphic and have been metamorphosed 1.1 to 0.8 b.y. B. P. and again during the Paleozoic approximately 0.50 to 0.23 b.y. B. P. These rocks are unconformably overlain by sedimentary and volcanic rocks which have a metamorphic history restricted to the Paleozoic. The distribution of older, polymetamorphic Precambrian rocks in New England and in the central Appalachians is moderately well known. One problematic area is southeastern Massachusetts where Rb-Sr whole rock ages on granites are near a 540 m.y. isochron (Fairbairn and others, 1965). Although these rocks are shown on the map as Paleozoic granites, further work in this area may conclusively determine a Precambrian age. The distribution of Precambrian rocks in the region south of the Potomac may more accurately reflect the extent of geologic mapping and radiometric age determinations rather than the true distribution of older Precambrian rocks. Recent mapping by Espenshade and Rankin (1970) revealed a large area of Precambrian rocks within the Inner Piedmont of North Carolina and Virginia which had not been previously described.

Although the degree of Precambrian metamorphism is variable within the polymetamorphic belt, the greenschist facies is absent throughout. Relict orthopyroxene and sillimanite in quartzo-feldspathic rocks are present in a wide area from the Hudson highlands of New York southward to about the North Carolina-Virginia boundary. Retrograde rocks similar to charnockites have been described in the core of the Blue Ridge anticlinorium (Bloomer and Werner, 1955). Relict orthopyroxene (dotted overprint) survives only in the western part of the older Precambrian belt where the Paleozoic metamorphic overprint is in the lower greenschist facies (an important exception being the Wilmington complex described by Ward, 1959). Consequently it is difficult to depict the earlier distribution of the granulite facies of metamorphism. The prevalence of a granulite mineral facies and the general radiometric age bracket for these rocks suggest that they are broadly correlative with rocks of the New Jersey highlands and the Adirondacks in New York.

PALEOZOIC METAMORPHIC BELTS

In New England and in the southeastern Appalachians, three major longitudinal axes of higher grade metamorphism (amphibolite and granulite mineral facies) of Paleozoic age are separated by areas of lower grade metamorphism (greenschist facies and garnet zone of amphibolite facies). In New England, these three belts include an outer or northwestern belt extending from the Manhattan prong northward through the core of the Green Mountain anticlinorium, a central belt comprising central Connecticut and Massachusetts, New Hampshire, and western Maine, and finally a southeastern belt, including Rhode Island, eastern Massachusetts, and the southern tip of Maine. Analogous belts in the southeastern Appalachians are a western belt in the Blue Ridge anticlinorium of North Carolina and Georgia, a central belt or Inner Piedmont extending from Alabama northeast through central Virginia to southeastern Pennsylvania, and a poorly exposed southeastern belt extending from Macon, Ga., through Columbia, S. C., to eastern North Carolina and east-central Virginia.

The persistence of metamorphic axes along linear belts within the Appalachians over great distances poses important problems in interpretation. Are the patterns principally related to thermal distributions during the Paleozoic Era or are they a result of structural deformation after regional metamorphism over the entire area? If the linear belts were of thermal rather than of mechanical origin in terms of their present outcrop pattern, were the belts formed simultaneously or as a result of successive thermal migrations in time? At present there seems to be no clear answer to these questions. In New England, the linear belt of greenschist along the east border of the Green Mountain anticlinorium is intimately related to thrusting. Thompson and others (1968) have demonstrated that isograds have been overturned and strongly deformed by later doming and emplacement of nappes derived from a previously heated easterly source. On the other hand, Clark and Kulp (1968) in a study of the isotopic age of metamorphism in western Connecticut and southeastern New York found three periods of metamorphism within the outer or northwestern belt of the New England Appalachians with ages of 480–460, 360, and 255 m.y. These age groups translate successively from northwest to southeast. A metamorphic event with an age of 270–230 m.y. has been associated in New England with the southeastern belt (Hurley and others, 1960; Faul and others, 1963), whereas an age of 400–350 m.y. seems well established for the metamorphic event in the central belt (Faul and others, 1963; Zartman and others, 1965).

In the southeastern Appalachians, relationships are broadly analogous. The western metamorphic belt in the Blue Ridge anticlinorium is separated from the central metamorphic belt of the Inner Piedmont both by a lower grade kyanite-staurolite zone and by a profound structural dislocation (the Brevard zone). In the western belt, an earlier metamorphism with a minimum age of 460 m.y. has been overprinted by a metamorphic event in the general range of 380–360 m.y. (Long and others, 1959). Throughout the southeastern Appalachians, histograms of all dates from all areas point to a pronounced maximum for a 360-m.y. event (Hadley, 1964). However, the eastern metamorphic belt at Raleigh, N. C., and Columbia, S. C., is closely associated with granites dated at 260–230 and 230 m.y., respectively (Long and others, 1959; Kulp and Eckelmann, 1961).

The major metamorphic patterns in the southeastern Appalachians are remarkable in that the isograds do not form concentric patterns about each other but close on themselves (for example, the sillimanite isograd in the Inner Piedmont belt and the garnet isograd in the James River synclinorium in west-central Virginia). Such a pattern is more suggestive of later broad-scale arching of the metamorphic terrane which grossly distorted the shapes of the isograds so that they resemble patterns of plunging anticlines and synclines.

In 1961, Miyashiro proposed the term metamorphic facies series to describe sets of mineral facies characteristic of a unique geothermal gradient operative during the metamorphism of a given terrane. He also documented evidence that on the Pacific margins, metamorphic belts of nearly synchronous age are present in pairs so that the outer or seaward belt was metamorphosed by a high P/T geothermal gradient, whereas the inner or landward belt was metamorphosed by a low P/T geothermal gradient. Zwart (1967) has characterized the metamorphic belts of Europe in terms of facies series; although clearly defined facies series are present in Europe, the presence of paired belts was not demonstrated. The greater part of the Appalachians within the United States has the classical barrovian type of prograde metamorphism (where mineral zones are chlorite, biotite, garnet, staurolite, kyanite, and sillimanite) designated as an intermediate temperature, intermediate pressure facies series. However, in central New England, the transition of kyanite to sillimanite is replaced by the transition of andalusite to sillimanite indicating a change to a higher geothermal gradient. A heavy dashed line marks the common boundary between the two facies series (Thompson and Norton, 1968). The change from an intermediate P/T to a low P/T facies series is noteworthy in that the change is transverse to structural and metamorphic trends rather than parallel as in the paired metamorphic belts of the Pacific rim described by Miyashiro.

The granulite metamorphic facies, defined by the breakdown of muscovite + quartz to orthoclase + sillimanite is widely developed in New England (Evans and Guidotti, 1966; Lundgren, 1966) but is absent in the southeastern Appalachians. Cordierite, cordierite-anthophyllite, and andalusite-bearing assemblages are widely developed in New England. South of the Potomac, however, cordierite almost vanishes, although several localities are known (Salotti and Fouts, 1967). Andalusite is very rare in greenschist rocks of Georgia and Alabama. These data seem to indicate that higher temperatures and lower pressures prevailed in metamorphism in New England than in the southeast.

A high geothermal gradient in New England qualitatively is suggested by the absolute spacing of garnet and sillimanite isograds. In New England the garnet and sillimanite isograds are often separated by only a few miles, whereas in most of the southeast, the separation is on the order of tens of miles. Although structural complications undoubtedly play a role in the distribution of the isograds and on their juxtaposition, such a general characteristic over hundreds of miles of metamorphic terrane is more likely related to a geothermal gradient higher in New England than in the southeast.

Calc-alkalic plutonic rocks are shown in pink. No distinction is made with regard to the age of these rocks; all are believed to be of Paleozoic age. Correlation of areas of intense plutonic activity and of sillimanite produced by regional metamorphism is not good when considering the entire Paleozoic Era. Post-Ordovician granites of New England transect isograds bounding the northern and northeastern limits of the "sillimanite plateau." In the southeastern Appalachians, the large plutonic belt near Charlotte, N. C., is east of the sillimanite zone in the Inner Piedmont. Sillimanite occurrences in eastern North Carolina and in Maryland are more closely related to later doming than to plutonic activity.

However, a much better correlation between plutonic activity and metamorphism is observed for a few specific areas. As pointed out by Thompson and Norton (1968) the New Hampshire Plutonic Series defined by Billings (1937, 1956) crops out within areas of higher metamorphic grade. In northern Vermont the sillimanite isograd is deflected around small plutonic bodies in a pattern more characteristic of contact rather than regional metamorphism. In North Carolina the Raleigh area is underlain by a large batholithic complex which is also enclosed by kyanite and garnet isograds (Parker, 1968).

Ultramafic bodies are not shown. Outcrops of these rocks have been compiled by Larrabee (1966). It is interesting to note that the great majority of ultramafic bodies are associated with the westernmost metamorphic culmination both in New England and in the southeastern Appalachians in or near a terrane underlain by a Precambrian continental crust.

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PRINCIPAL SOURCES OF INFORMATION USED IN COMPILATION

The principal sources for data used in the compilation are listed by area below. The compilations by Goldsmith (1964) and Thompson and Norton (1968) of Paleozoic metamorphism in New England have been an invaluable aid, and the author wishes to make a special acknowledgment of these papers. Several compilations and excellent summary papers are available for New England and New York. However, in the southeastern Appalachians, few such papers have been written, and the reference list is correspondingly longer for such areas.

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