

The Paleozoic and Mesozoic Rocks;
A Discussion to Accompany the
Geologic Map of the
United States

GEOLOGICAL SURVEY PROFESSIONAL PAPER 903



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By PHILIP B. KING *and* HELEN M. BEIKMAN

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THE PALEOZOIC AND MESOZOIC ROCKS; A DISCUSSION TO ACCOMPANY THE GEOLOGIC MAP OF THE UNITED STATES

By PHILIP B. KING and HELEN M. BEIKMAN

ABSTRACT

This report deals with the Paleozoic and Mesozoic rocks that are exposed within the area covered by the Geologic Map of the United States and treats them in terms of the map legend. They are therefore discussed in chronological order, from oldest to youngest. Under each age, the stratified rocks in the most complete sequences are described first, followed by combinations such as Devonian and Silurian, Jurassic and Triassic, and finally by lower Paleozoic, upper Paleozoic, and lower Mesozoic. Next, special lithologic types of each age are taken up, the continental deposits, eugeosynclinal deposits, and volcanic rocks. At the end of the discussions of both Paleozoic and Mesozoic Eras are summaries of the plutonic rocks formed during those eras.

The better known and most extensively exposed rocks—the Paleozoic sequence of the Central Interior and the Cretaceous of the Coastal Plains and Rocky Mountains—are summarized briefly, as these are well covered in an extensive literature. More details are given for rocks of each age in the Appalachian and Cordilleran mountain belts, especially the eugeosynclinal deposits, because they have been poorly understood until recently.

Although the text is designed primarily to justify the representation of the units shown on the map, it also amplifies the necessarily brief descriptions of the units in the legend, and sufficient data are given to indicate the general lithologies of the units as exposed in the different areas, which on the map are shown primarily as time-stratigraphic rather than rock-stratigraphic entities.

INTRODUCTION

The following text is a discussion and exposition of the different units of Paleozoic and Mesozoic rocks that are represented on the Geologic Map of the United States. It is thus partly an expansion and justification of the legend of the Geologic Map, but something is also said regarding the nature and origin of the rocks involved and the stratigraphy of the stratified rocks. On the other hand, it is not a complete treatise on these rocks, for such a treatise would far exceed the objectives of the report.

In the text, the better known and most extensively exposed sequences are summarized briefly and with little documentation: the Paleozoic of the Central Interior and the Cretaceous of the Coastal Plains and Rocky Mountains. Many accounts of these rocks have been published, and they are well described in the more detailed textbooks of historical geology and

stratigraphy—for example, those of Dunbar (1969), Kay and Colbert (1965), and Kummel (1970). Correlation of the formations of the Paleozoic and Mesozoic systems, with useful annotations, may be found in the charts prepared by committees of the National Research Council that were published between 1940 and 1960 by the Geological Society of America. In addition, some regional surveys are available, the most notable of which is the Geologic Atlas of the Rocky Mountain region (Mallory, 1972).

More details and more documentation are given of the complex Paleozoic and Mesozoic rocks in the Appalachian and Cordilleran mountain belts in the east and west, understanding of which is now increasing as a result of geologic work during the last few decades. These rocks are partly eugeosynclinal, partly crystalline, are generally poorly fossiliferous, and contain embedded plutonic rocks. Besides new fossil discoveries, much light has been thrown on the ages and relations of these rocks by radiometric dating, as indicated by citations in the text.

The Geologic Map represents only the surface geologic features of the country, and the text accordingly deals only with the exposed rocks; little or no mention is made of the concealed rocks that have become known from subsurface studies.

The text is illustrated primarily by small-scale maps of the United States, which show the extent of the different Paleozoic and Mesozoic systems or other gross units represented on the Geologic Map.

CAMBRIAN

The Cambrian System, the lowest unit of the Phanerozoic Eon, is represented on the Geologic Map of the United States by marine stratified rocks (C), with basal Lower Cambrian clastic rocks (Cq) differentiated in places; by eugeosynclinal deposits (Ce) and associated volcanic rocks (Cv); and by a few Cambrian granitic rocks (Cg) described with the other Paleozoic plutonic rocks in a later section.

MARINE STRATIFIED ROCKS (€)

Cambrian strata are most extensively exposed in the cratonic area of the Central Interior Region (fig. 1). Here they form a wide band along the southern margin of the Precambrian rocks of the Lake Superior Region, from Minnesota across Wisconsin into the Upper Peninsula of Michigan; they also form an area surrounding the Precambrian rocks in the Ozark dome in Missouri. Smaller bands of outcrop adjoin the Precambrian of the Adirondack dome in New York State, the Arbuckle and Wichita Mountains in southern Oklahoma, and the Llano uplift in central Texas. Cambrian rocks also form long narrow bands in the folded and faulted miogeosynclinal belt of the Appalachian Region east of the Central Interior Region.

The Cambrian System is extensive as well in the Cordilleran Region west of the Central Interior, but for the most part its outcrops and those of succeeding lower Paleozoic systems are so narrow and discontinuous that they are all merged on the Geologic Map into a single unit (1P). In a few areas, however, Cambrian outcrops are sufficiently extensive for representation, notably in the Great Basin and in the thrust belt extending northward from southeastern Idaho into northwestern Montana. The Cambrian is also shown separately in Arizona, from the Grand Canyon to the southeastern part of the State; the thin overlying Devonian System, elsewhere classed as lower Paleozoic, is here merged with the upper Paleozoic (uP).

The Cambrian is the oldest system containing shelly fossils suitable for stratigraphic analysis, and it has been elaborately zoned and correlated. At least 10 fossil zones are recognized. The Cambrian has been divided into a Lower, Middle, and Upper Series—sometimes termed the Waucoban, Albertan, and Croixan (or St. Croixan) (Lochman-Balk, 1972, p. 61). These are not represented on the Geologic Map, for the large outcrops in the Central Interior are all Upper Cambrian, and the Middle and Lower Cambrian Series appear only in the mountain belts to the east and west, where the outcrop bands are too narrow to be subdivided.

In most places the Cambrian System overlies the Precambrian with a large hiatus and profound unconformity. Throughout the Central Interior, Upper Cambrian lies on deformed rocks 500 to 2,000 m.y. (million years) older (Precambrian Y, X, and W). In contrast, in some of the geosynclinal sequences in the mountain belts to the east and west, where both Lower Cambrian and Precambrian Z stratified rocks are present, the stratigraphic break between them is slight or absent, creating problems in classification. These problems are most acute in the southwestern part of the Great Basin, between Las Vegas, Nev., and the Inyo Mountains,

Calif., where fine-grained Precambrian Z and Lower Cambrian strata form a conformable sequence as much as 21,000 ft (6,400 m) thick, with diagnostic Cambrian fossils only in the upper third. Here and elsewhere, however, the problematical rocks form outcrops so small on the scale of the Geologic Map that for our purposes they can be disregarded.

The top of the Cambrian System is generally conformable with the Ordovician but is definable by paleontological means. The "Ozarkian System" which was proposed by E. O. Ulrich in the early part of the century for a unit between the Cambrian and the Ordovician has now been discredited, and its proposed components have been assigned to one system or the other. The only difficulties in mapping the boundary are in parts of the Appalachian miogeosyncline where Upper Cambrian and Lower Ordovician rocks are parts of a thick mass of carbonates, as in such units as the Knox Group (Knox Dolomite of older reports) in the Southern Appalachians. By detailed stratigraphic work the Cambrian part of the Knox (Copper Ridge Dolomite or Conococheague Limestone) can be separated from the Ordovician part, but components of the two ages are not everywhere shown on the source maps; in such places they have been divided arbitrarily on the Geologic Map. From New Jersey northward, however, the outcrop belts are narrower and more complex, and so it has been necessary to merge the Cambrian and Lower Ordovician carbonates into a single unit (O€), even though data for their separation are available in places (see section "Ordovician and Cambrian").

The miogeosynclinal sequence in the Appalachian Region begins with Lower Cambrian clastic deposits (€q), which are separately shown on the Geologic Map where their outcrop belts are sufficiently wide. They are typified by the Chilhowee Group of Tennessee, Virginia, and Maryland, 3,000 ft (900m) or more thick, with conglomerates and arkoses in the lower part and prominent quartzite layers separated by shale and siltstone above. Similar rocks flank the western edges of the Green Mountains and Berkshire Hills uplifts in western New England, with the thick Cheshire Quartzite at the top. Shelly fossils of the *Olenellus* zone occur only in the upper formations of the clastic deposits, although trace fossils such as *Scolithus* are found much lower. The lowest parts are unfossiliferous, hence are classed as Cambrian (?). Throughout the length of the Appalachian miogeosyncline, the clastic deposits are succeeded abruptly by a great carbonate sequence more than 10,000 ft (3,000 m) thick that includes the remainder of the Lower Cambrian, the Middle and Upper Cambrian, and the Lower Ordovician Series.

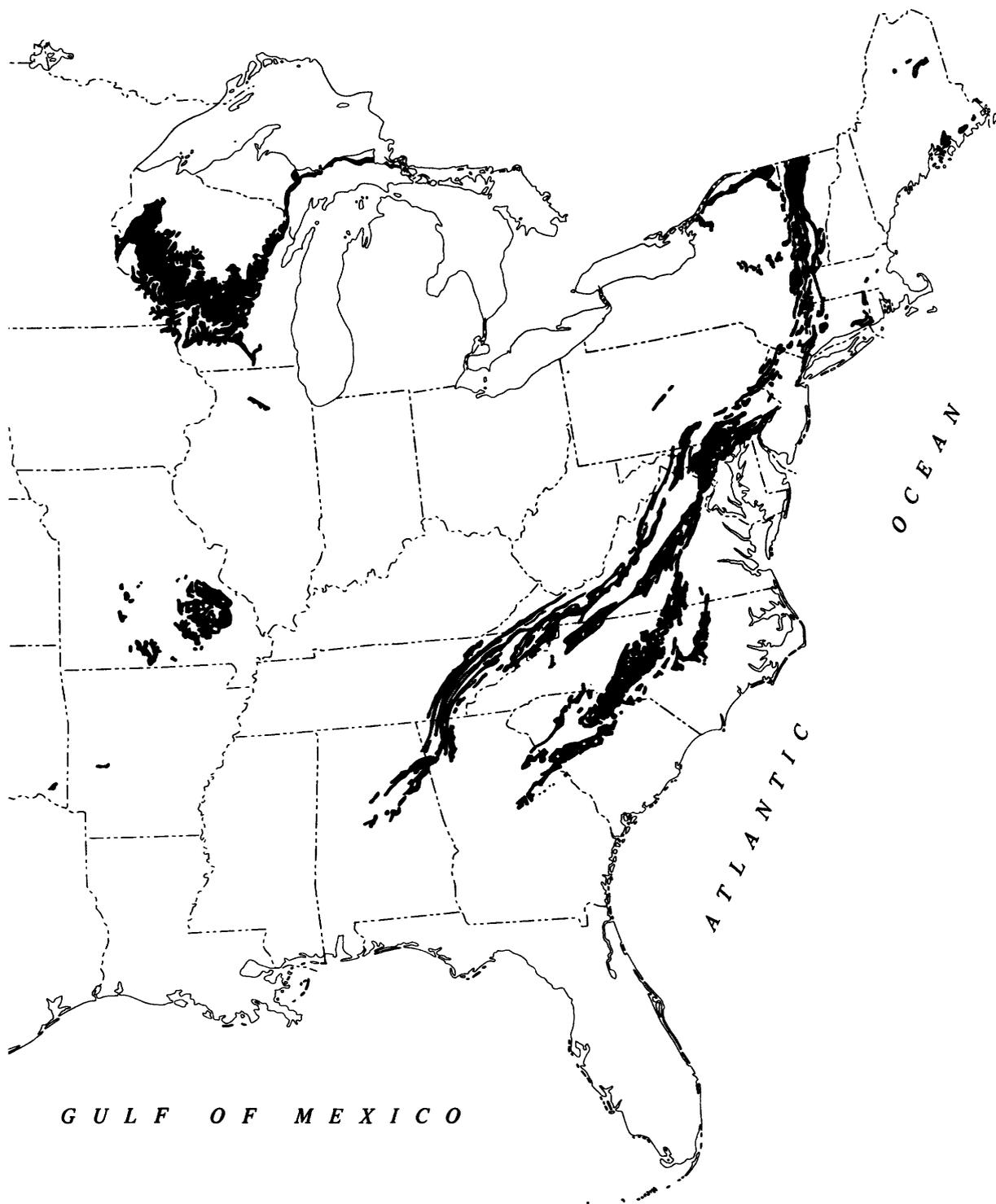


FIGURE 1.—Eastern United States, showing areas mapped as Cambrian on Geologic Map of United States. Includes units of marine stratified rocks (C), basal Lower Cambrian clastic rocks (Cq), Lower Ordovician and Cambrian carbonate rocks (O-C), eugeosynclinal deposits (Ce), and volcanic rocks (Cv).

The miogeosynclinal sequence of the Cordilleran Region, in the Great Basin west of the "Wasatch line," also begins with Lower Cambrian clastic deposits known from place to place as the Brigham, Tintic, and Prospect Mountain Quartzites. For consistency, it would have been interesting to have separated these on the Geologic Map, but although they are as thick and prominent as those in the Appalachian miogeosyncline, their outcrops are more discontinuous and patchy and too small for representation. In this region, as in the Appalachian miogeosyncline, the clastic deposits are succeeded by carbonate rocks, in this case of Middle and Late Cambrian age, with thicknesses in the classic sections in the House Range, western Utah, and the Eureka district, east-central Nevada, of 8,200 and 5,400 ft (2,500 and 1,600 m), respectively.

Throughout the Central Interior Region, the basal Cambrian deposits are also sandstone, but they are the basal deposits of the cratonic sequence and are all of Late Cambrian age except in the extreme west (parts of the Rocky Mountains and Colorado Plateau), where some of them are as old as Middle Cambrian. In northeastern New York State the Potsdam Sandstone on the flanks of the Adirondack dome is closely adjacent to the Cheshire Quartzite of the basal Lower Cambrian clastic deposits across Lake Champlain to the east, but it is of Late Cambrian age like the other basal cratonic deposits farther west in the Central Interior. The type Croixan Series in the border region of Minnesota and Wisconsin is nearly all different varieties of sandstone and about 1,000 ft (300 m) thick; fossils throughout it permit its division into three stages and eight zones (Bell and others, 1956).

Cambrian (C) is shown on the Geologic Map in the two core areas of the Ouachita Mountains foldbelt—the Broken Bow uplift of southeastern Oklahoma and the Benton uplift of southwestern Arkansas. The unit so shown is the Collier Shale, traditionally classed as Cambrian but from which early Ordovician (Tremadocian) conodonts have recently been collected (Repetski and Ethington, 1973). The age designation on the map is therefore erroneous, but it at least illustrates the structurally highest parts of the foldbelt.

EUGEOSYNCLINAL DEPOSITS (Ce)

Cambrian eugeosynclinal deposits are shown on the Geologic Map throughout much of the length of the Appalachian Region, east of the miogeosynclinal belt. In the Cordilleran Region, where present, they are merged with the other lower Paleozoic eugeosynclinal deposits (lPe). Characteristic components of the eugeosynclinal deposits are volcanic rocks (Cv), which are differentiated on the Geologic Map where they underlie sufficiently large areas.

Cambrian rocks of eugeosynclinal facies form an outcrop belt in western New England that extends along the east flank of the Green Mountains and other Precambrian uplifts from the Canadian border through Vermont and Massachusetts to Connecticut (fig. 2). In Vermont, north of the plunging end of the Precambrian, Cambrian rocks extend across the Green Mountains anticlinorium to adjoin the Cambrian miogeosynclinal rocks, and so a transition between them can be worked out (Cady, 1960, p. 539–543). The dominant carbonate rocks of the latter change eastward into argillaceous and coarser clastic rocks (now schistose), with lenticular volcanic units, and the sequence thickens dramatically to more than 20,000 ft (6,000 m). Fossils are virtually absent, but correlations can be reasonably established with the fossiliferous miogeosynclinal sequence to the west and with dated units along the strike in Canada to the north, suggesting that Lower, Middle, and Upper Cambrian Series are all represented.

Cambrian eugeosynclinal deposits are also mapped in the Taconic area west of the Green Mountains in western New England and eastern New York State, where they are allochthonous on the Cambrian and Ordovician miogeosynclinal rocks. Here again, the sequence is dominantly argillaceous or silty, with minor coarser layers; however, it is no more than a few thousand feet (300–600 m) thick, and interbedded volcanic rocks are rare (Zen, 1967, p. 14–22). Parts of the sequence are fossiliferous and indicate that much of it is of Lower Cambrian age, although Middle and Upper Cambrian fossils have been found in places. According to present beliefs, the rocks of the Taconic sequence formed in the transition zone between the miogeosynclinal carbonates and the thick eugeosynclinal rocks at a site a little east of the present Green Mountains axis and were transported as one or more slices, largely by gravity sliding, onto a sea floor where Middle Ordovician deposits were still accumulating.

Small areas of Cambrian rocks are mapped much farther east in New England, in eastern Maine and Massachusetts; however, most of these rocks are poorly defined paleontologically, and their age is suggested mainly by their relations to overlying beds or by radiometric dating. The Grand Pitch Formation at the base of the eugeosynclinal sequence in northeastern Maine is a red slate containing the trace fossil *Oldhamia*, which occurs elsewhere in Cambrian rocks. South of Boston in Massachusetts are the much better dated Hoppin Slate and Weymouth Formation with Lower Cambrian fossils and the Braintree Slate with Middle Cambrian *Paradoxides*, the faunas being of Atlantic facies, unlike the North American faunas in the Appalachian miogeosyncline to the west. Unfortu-

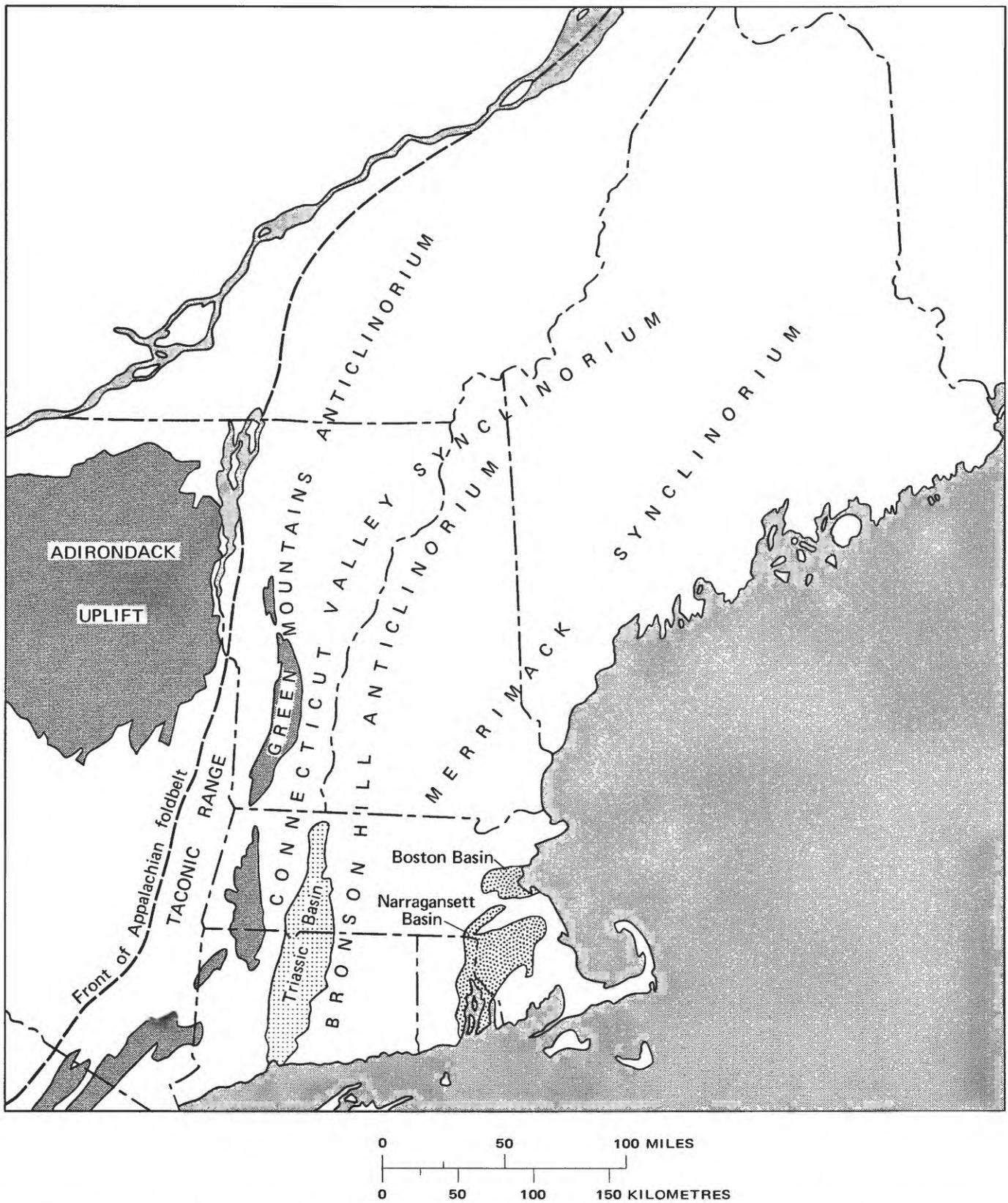


FIGURE 2.—New England, showing positions of tectonic features referred to in the discussions of the Cambrian, Ordovician, Silurian, and Devonian eugeosynclinal rocks.

nately, all these occurrences are very small—some little more than specimen localities—and so it is impractical to mark them on the Geologic Map. The map indicates as Cambrian the somewhat larger outcrops of the Westboro Quartzite northwest of Boston, but its age is uncertain; it may be of late Precambrian age, as was deduced by Emerson (1917, p. 24).

In the Central Appalachians, the principal eugeosynclinal deposit of Cambrian age is the Glenarm Series of the Piedmont province in Maryland and adjacent States (Hopson, 1964, p. 54–128; Higgins, 1972). At the base, next to the domes of Precambrian Baltimore Gneiss, are the Setters Formation (quartz schist and quartzite) and the Cockeysville Marble, followed by the great clastic mass of the Wissahickon Formation, more than 20,000 ft (6,000 m) thick. Although the Wissahickon consists of high-grade metamorphic rocks, it contains abundant relict sedimentary structures which indicate that it is a flysch¹ or turbidite deposit. Locally interbedded in the Wissahickon is the thick lens of the Sykesville Formation, once interpreted as a granitic intrusive but actually a coarse submarine slide derived from an eastern source, containing heterogeneous clasts and blocks of sedimentary and metamorphic rocks. Toward the southeast, next to the Coastal Plain, the Wissahickon interfingers with and is overlain by the James Run Formation of volcanic and volcanoclastic rocks. In the western Piedmont of Maryland, the Wissahickon is replaced by and partly overlain by shallow-water phyllites, marbles, and basalt flows (Ijamsville Phyllite, etc.) which are represented on the Geologic Map as Cambrian stratified rocks (⊖).

The age of the Glenarm Series has long been disputed, being placed in late Precambrian or early Paleozoic time. Hopson (1964, p. 203–207) proposed a late Precambrian age because enclosed granitic plutons have ages of 470 to 550 m.y. and of about 425 m.y. The events separating the oldest of these plutons from the formation of the Glenarm Series were inferred to have been sufficiently prolonged that the series must have formed before Cambrian time. However, Higgins (1972, p. 1008–1009) demonstrated that the older group of supposed granitic intrusives (470–550 m.y.) is actually an assemblage of metamorphosed sediments; hence the dates define the maximum age of the Glenarm, or perhaps its true age—that is, Cambrian rather than Precambrian.

¹The term "flysch" is derived from the original Flysch of the European Alps and is used consistently in this report for a peculiar assemblage of thinly interbedded sandy and shaly rocks; the sandy rocks commonly show grading and other structures which suggest that they were derived from turbid flows, and the shaly rocks represent interludes of pelagic sedimentation. Flysch is a deep-water deposit that commonly accumulated in linear troughs in mobile belts. Not included are other synorogenic deposits (to which the term has sometimes been misapplied), many of which formed in quite different environments.

Southwestward in central Virginia, in apparent continuity with the Glenarm, is the Evington Group of the Lynchburg area (Espenshade, 1954, p. 14–21; Brown, 1958, p. 28–38). On the flank of the Blue Ridge, resting on the Precambrian Z Lynchburg Formation (or the Catoctin Greenstone, where present), is the Candler Phyllite, about 5,000 ft (1,500 m) thick, which is followed by several thousand feet of more varied strata—schist, marble, and quartzite—with about 1,000 ft (300 m) of greenstone metavolcanic rocks at the top. The Evington Group contains no fossils, and no radiometric dates are available; from its relations to the Lynchburg and by comparison with the Glenarm, it is presumably early Paleozoic (Cambrian?) and is so represented on the Geologic Map (⊖e).

Still farther southwestward, near the Virginia–North Carolina border, and more or less in continuity with the Evington Group, is the Alligator Back Formation (Rankin and others, 1973, p. 17–19). It overlies the Precambrian Z Ashe Formation (= Lynchburg Formation) and consists of laminated graywacke and pelite with "pinstripe" structure; volcanic rocks interfinger northeastward. Although there is no clear evidence of age, it is likewise indicated as Cambrian (⊖e) on the Geologic Map.

A much larger area of Cambrian eugeosynclinal deposits (⊖e) forms the Carolina Slate Belt of the Southern Appalachians, extending as a wide band across the Piedmont province from southern Virginia through North and South Carolina to eastern Georgia (Conley and Bain, 1965; Sundelius, 1970). In central North Carolina the band is 130 mi (210 km) wide, but it narrows to the northeast and southwest. The Slate Belt contains a sequence of gently deformed low-grade metamorphic clastic and volcanic rocks more than 30,000 ft (9,100 m) thick. These are adjoined to the northwest and southeast by higher grade metamorphic rocks, in part the metamorphosed equivalents of the Slate Belt rocks, but probably mainly older. They are intruded here and there by granitic and mafic plutons with ages of 520 to 595 m.y. (Fullagar, 1971, p. 2852–2854). Areas of low-grade clastic and volcanic rocks like those in the Slate Belt also occur farther southeast and are encountered in many drill holes beneath the Atlantic Coastal Plain.

In North Carolina, a rather consistent stratigraphy can be worked out and mapped in the rocks of the Slate Belt. Below (with the base not exposed) is the thick Uwharrie Formation of rhyolitic and rhyodacitic flows and pyroclastics. Above are thinner units of laminated shales, mudstones, and siltstones, alternating with volcanic-rich units. The subdivisions are not shown on the Geologic Map, but the volcanic rocks (⊖v) are separated where they underlie sufficiently large areas. The

age of the rocks in the Slate Belt can be indicated only in a general way. At one locality in southern North Carolina, are a few *Paradoxides* of probably Middle Cambrian age (St. Jean, 1973). From rocks in the same general area, an Ordovician age of 440 to 470 m.y. was obtained by the lead-alpha (Pb/alpha) method, but this age seems to be unreliable and too young. A considerable part of the sequence is probably late Precambrian (Z). In northern North Carolina, on the Little River 12 miles (20 km) north of Durham, Lynn Glover III and his associates have found Ediacaran (= Vendian) type fossils, which are the imprints of primitive wormlike animals on the bedding surfaces of volcanoclastic strata. At the north end of the belt in Virginia, radiometric ages in excess of 600 m.y. have been obtained from the slate belt rocks (Glover and Sinha, 1973).

In the Cordilleran Region, the only authentic Cambrian eugeosynclinal deposits known to us are the Scott Canyon Formation which forms a small area in the south part of Battle Mountain, north-central Nevada. Limestones interbedded in its cherts, shales, and greenstones contain archeocyathids of Lower or Middle Cambrian age. It is mapped as part of the lower Paleozoic eugeosynclinal deposits (1P_e). The Cambrian (C) shown in Battle Mountain and nearby ranges is the Harmony Formation, an arkosic turbidite of Late Cambrian age, which is classed as a "transitional" facies rather than eugeosynclinal (Roberts and others, 1958, p. 2829-2830), hence is included in the normal stratified sequence on the Geologic Map.

ORDOVICIAN AND CAMBRIAN

MARINE STRATIFIED ROCKS (O-C)

As indicated above, the Appalachian miogeosynclinal rocks include a thick sequence of carbonates that extends from the Lower Cambrian into the Lower Ordovician System. In the Central and Southern Appalachians, it has been possible to separate the Cambrian and Ordovician components on the Geologic Map, but from New Jersey northward the outcrop belts are narrower and more complex and have been merged into a single unit (O-C).

In New Jersey and southern New York, the subdivisions are apparent in places but have not been worked out regionally, and they are shown as undivided units on the source maps—the Kittatinny and Wappinger Limestones of the northwestern belts and the Inwood and Stockbridge Marbles of the metamorphic belt east and southeast of the Hudson Highlands. Farther north, in the Champlain Lowlands of Vermont and adjacent New York, the subdivisions of the Cambrian and Lower Ordovician carbonates have been worked out

and mapped in detail (see Geologic Map of Vermont, 1961) but cannot be represented on the scale of the Geologic Map.

In the eugeosynclinal area of New England, the source maps likewise indicate some of the units as "Ordovician-Cambrian" (meaning Ordovician or Cambrian), but these have been arbitrarily assigned to one system or the other on the Geologic Map.

ORDOVICIAN

The Ordovician System is represented on the Geologic Map of the United States by marine stratified rocks (O), divided in part into Lower, Middle, and Upper Series (O₁, O₂, O₃), and by eugeosynclinal deposits (Oe) with associated volcanic rocks (Ov). The Ordovician is shown separately in the eastern two-thirds of the country; from the Rocky Mountains westward it is merged with the other lower Paleozoic systems (1P, 1P_e).

MARINE STRATIFIED ROCKS

The most extensive exposures of Ordovician strata are in the cratonic area of the Central Interior Region, where they are nearly flat lying or are gently tilted on the flanks of the broad domical uplifts (fig. 3). In the north, they form a broad band of outcrop between the Cambrian and Silurian sequences around the west, south, and east flanks of the Wisconsin dome, extending from Minnesota to the Upper Peninsula of Michigan and as far south as Illinois. Farther south, they form much of the surface of the Ozark dome in Missouri and Arkansas—largely Lower Ordovician with the Middle and Upper Ordovician Series in narrow bands around the edges. Middle and Upper Ordovician rocks form the crestal areas of the Cincinnati and Nashville domes farther east, where the Lower Ordovician rocks is not exposed. The three series also encircle the Adirondack dome in New York State, and smaller Ordovician outcrops occur in the Arbuckle and Wichita Mountains and the Llano uplift in Oklahoma and Texas. Intervening areas in the Central Interior are covered by younger strata, but the presence of Ordovician rocks beneath them is known from drilling.

Ordovician rocks also crop out in long bands throughout the length of the miogeosynclinal belt of the Appalachian Region east of the Central Interior Region and emerge in the core areas of the Ouachita Mountains foldbelt to the south.

The three series of the Ordovician System are shown separately throughout the Central Interior, as well as in parts of the Appalachian miogeosynclinal belt in New York and Pennsylvania. In the remainder of the miogeosynclinal belt, the Ordovician outcrop bands are

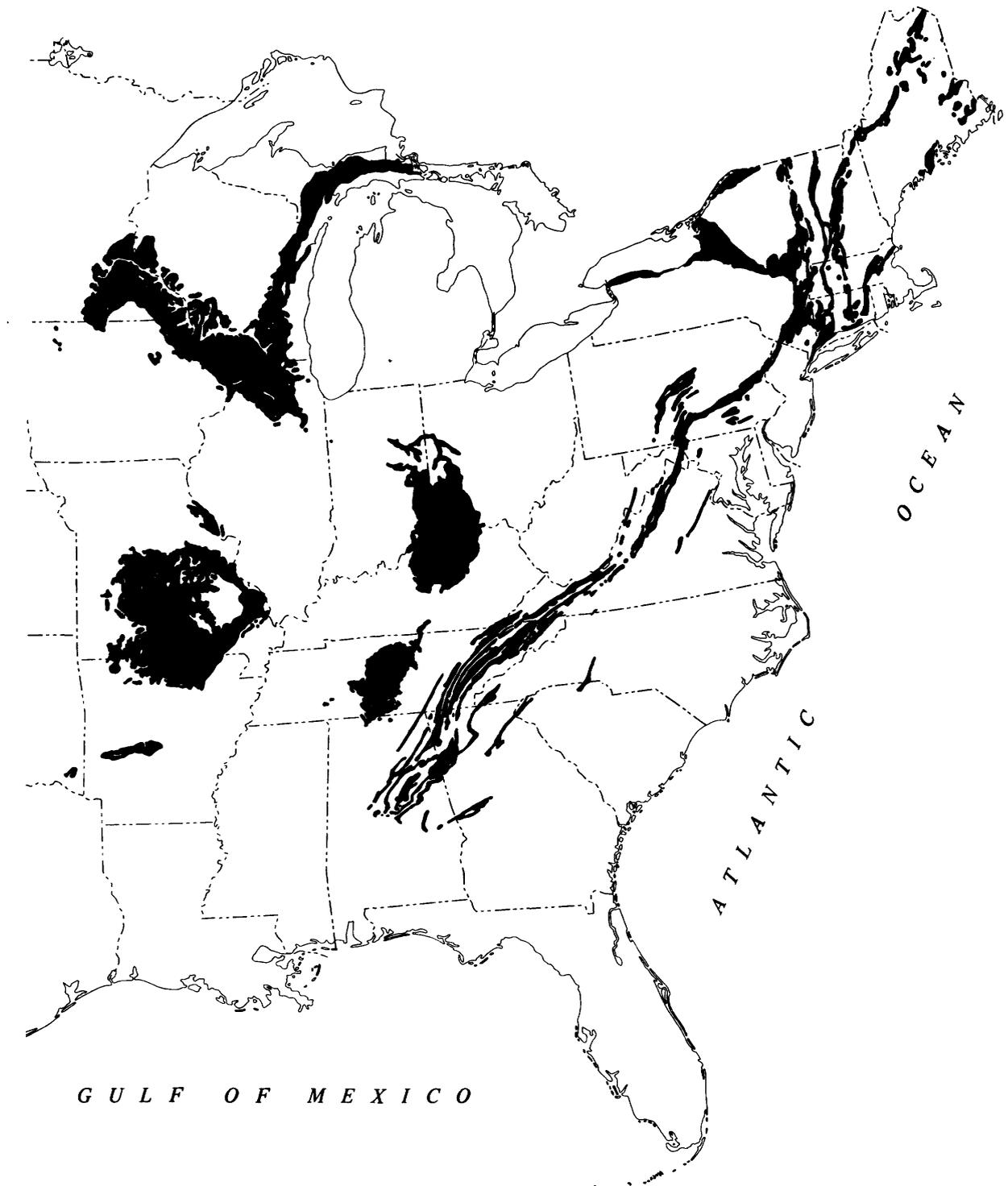


FIGURE 3.—Eastern United States, showing areas mapped as Ordovician on Geologic Map of United States. Includes units of marine stratified rocks (O) and their subdivisions (O₁, O₂, O₃), eugeosynclinal deposits (O_e), volcanic rocks (O_v), and a few of lower Paleozoic (1P) in the Southern Appalachians.

too narrow for subdivision and are shown as a single unit (O). On the other hand, the Lower Ordovician Series in the Ozark dome forms such an extensive area that further separation is needed to illustrate the geology. Here, the series is divided at the base of the Jefferson City Dolomite into units O_{1a} and O_{1b}, although there are no fundamental paleontological or sedimentological differences between the two parts. (Somewhat similar subdivisions were made on the Geologic Map of 1932).

The Lower Ordovician or Canadian Series (O₁) is largely carbonate, much of it dolomite, which succeeds similar carbonates of the Upper Cambrian Series (as noted above). In many places the two components were not separated in early reports, resulting in units such as the Knox of the Southern Appalachians, the Arbuckle of the Arbuckle and Wichita Mountains, Oklahoma, and the Ellenburger of the Llano area, Texas; relations are now clarified, and these and similar units are classed as groups. Throughout the Appalachian miogeosyncline, the series is about 2,000 ft (600 m) thick, but it has a maximum thickness of about 5,000 ft (1,500 m) in the deep trough adjoining the Arbuckle and Wichita Mountains. It thins in the cratonic area, being about 1,000 ft (300 m) thick in the Ozark dome and no more than a few hundred feet thick on the flanks of the Wisconsin dome (Prairie du Chien Group).

The Middle Ordovician or Mohawkian Series (O₂)² is more varied, largely limestone and shale but with notable units of sandstone in the lower part. Its abundantly fossiliferous strata have been the field of labor of many paleontologists and stratigraphers, and it has been minutely subdivided and correlated from place to place. The details do not concern us here, but a few general items are worth noting.

In the northern Midwestern States, the basal Middle Ordovician unit is the Saint Peter Sandstone, a clastic sheet of vast extent probably derived from the Canadian Shield (Dake, 1921, p. 221-224). To the north it lies on a rough surface eroded on Lower Ordovician rocks, but southward it fingers out into carbonate formations.

Eastward in the Appalachian miogeosyncline, the Middle Ordovician limestones and shales with shelly fossils give way to shales and coarser clastic rocks in which the principal fossils are graptolites. These shaly rocks include some important belts of flysch, such as the Normanskill Formation of New York State and the Martinsburg Formation of the Central Appalachians

(which continues upward into the Upper Ordovician, although it is all marked as O₂ on the Geologic Map) (McBride, 1962, p. 39-43). These shaly rocks (O₂) form the autochthonous substratum of the allochthonous Taconic rocks in eastern New York and western New England. Southeast of the Hudson Highlands, they pass into a higher grade metamorphic facies (Manhattan and Berkshire Schists) which extends eastward in Connecticut to an obscure boundary ("Cameron's line"), possibly a thrust, which separates them from the eugeosynclinal Hartland Schist (O_e).

Graptolite shales with some interbedded sandstone also compose the Lower and Middle Ordovician Series in the Ouachita Mountains foldbelt (Mazarn Shale, Blakeley Sandstone, and Womble Shale).

The Upper Ordovician or Cincinnati Series (O₃) is typified by exposures in the Cincinnati dome of Ohio and adjacent States, where its shales and limestones (Eden, Maysville, and Richmond Groups) are richly fossiliferous. Other shales, the Maquoketa, form the Upper Ordovician in the northern Midwestern States. Farther southwest, the Upper Ordovician sequence (and part of the Middle Ordovician) is mainly cherty limestone, the Viola of the Arbuckle and Wichita Mountains, which passes into the Bigfork Chert in the nearby Ouachita Mountains. Eastward toward the Appalachian belt, the uppermost Upper Ordovician passes into redbeds, in part continental—the Queenston Shale of northwestern New York and the Juniata and Sequatchie Formations farther south—which are post-orogenic to the Taconian deformation in the foldbelt itself.

EUGEOSYNCLINAL DEPOSITS

Ordovician eugeosynclinal deposits and associated volcanic rocks (O_v) are mapped in numerous areas in all the New England States, but especially on the west and east flanks of the Connecticut Valley synclinorium, with smaller less continuous areas to the east and southeast. Their stratigraphy and ages are best deciphered in the north, where the rocks are least metamorphosed and fossils obtainable in places. The stratigraphy of the higher grade metamorphic rocks farther south, as in Massachusetts and Connecticut, is indicated by comparisons with or by actual tracing from these better known rocks.

The eugeosynclinal rocks of the Connecticut Valley are in a homoclinal belt that extends south from the Canadian border through Vermont and Massachusetts into Connecticut, between the Cambrian rocks of the Green Mountains and other uplifts on the west and the Silurian and Devonian rocks of the synclinorium; they are mainly phyllites and schists but include lenticular bodies of sandstone and volcanic rocks; in northern

²Terminology of the Middle Ordovician Series is confused. According to some usage (for example, Twenhofel and others, 1954), the Middle Ordovician is the Champlainian, which is subdivided into the Chazyan below and the Mohawkian (Black River and Trenton Limestones and equivalents) above. All these names are derived from the classic sequence in New York.

Vermont and adjacent Canada some of the units contain graptolites.

The eugeosynclinal rocks east of the Connecticut Valley from New Hampshire southward are in the Bronson Hill anticlinorium—actually a highly irregular chain of domes much entangled with plutons and with pronounced nappe structures. Volcanic components are much greater here than to the west; most of the sediments are tuffaceous, and the thick Ammonoosuc Volcanics occur near the middle (Billings, 1956, p. 12–21). The anticlinorium may have originated as a volcanic arc in the eugeosyncline. Above the Ammonoosuc is the Partridge Formation, a black sulfidic argillaceous rock that continues southward into the Brimfield Schist of Massachusetts. The Ordovician sequence in the Bronson Hill anticlinorium is more than 20,000 ft (6,000 m) thick, but its base is not exposed; it is overlain unconformably by the fossiliferous Silurian Clough Quartzite which also truncates the Highlandcroft Plutonic Series (P_{g1}), intrusive into the Ordovician.

Along the continuation of the belt across northern Maine, Middle Ordovician graptolites occur at various places in shales above the volcanic rocks. An interesting variant in northeastern Maine is the Shin Brook Formation of tuffaceous sediments and volcanic breccias that contains a large assemblage of Middle Ordovician shelly fossils (brachiopods, trilobites, and so forth), probably formed in a shoal area in the eugeosyncline (Neuman, 1964).

Small areas of Ordovician eugeosynclinal rocks are shown on the Geologic Map as overlying the Cambrian sequence in the allochthonous Taconic area of eastern New York. They are graptolite-bearing shales and graywackes like the Normanskill Formation of the surrounding autochthon but include strata of Early as well as Middle Ordovician age.

The only authentic Ordovician formation known to us in the eugeosynclinal area south of New England is the Arvonian Slate of central Virginia that contains abundant (though much deformed) shelly fossils of Middle or Late Ordovician age (Brown, 1969, p. 25–26); it lies unconformably on metamorphic and plutonic rocks of earlier Paleozoic age. Also shown as Ordovician (Oe) on the Geologic Map are the Quantico Slate south of Washington, D.C., and the Peach Bottom Slate of southern Pennsylvania, but although traditionally they have been correlated with the Arvonian, their age is less certain and they may be older (Higgins, 1972, p. 972). The existence of Ordovician rocks elsewhere in the Piedmont of the Central and Southern Appalachians is a possibility, but no evidence for them is available; present indications are that most of the Piedmont supracrustal rocks are older.

SILURIAN AND ORDOVICIAN

EUGEOSYNCLINAL DEPOSITS (SOe)

In northeastern Maine (Aroostook County) the hybrid category "Silurian and Ordovician" is used on the Geologic Map to designate the Carys Mills Formation and some related deposits. These form a sequence about 12,000 ft (4,000 m) thick of calcareous silty and sandy rocks that extends from the Middle Ordovician into the Lower Silurian Series (Caradoc to Llandover), as indicated by graptolites and other fossils (Pavrides, 1968, p. 8–13). Use of the hybrid term in this area demonstrates the lack of any Taconian orogenic activity and consequent structural discordance, such as occurs between the Ordovician and Silurian Systems in much of the remainder of New England. Although the Carys Mills is calcareous and lacks any volcanic material, it is not miogeosynclinal. It is, instead, a calcareous flysch laid down in the depths of a part of the eugeosyncline that was far from any tectonic or volcanic areas.

SILURIAN

The Silurian System is represented on the Geologic Map of the United States by marine stratified rocks (S), divided in part into the Lower, Middle, and Upper Silurian Series (S_1 , S_2 , S_3), and by eugeosynclinal deposits (Se) with associated volcanic rocks (Sv). The Silurian is shown separately in the northeastern third of the country; in the Southern Appalachians and the Ouachita Mountains it is combined with the Devonian (DS), and from the Rocky Mountains westward it is combined, where present, with the other lower Paleozoic systems ($1P$, $1Pe$).

MARINE STRATIFIED ROCKS (S)

As with the systems below and above, the Silurian is most extensively exposed in the cratonic area of the Central Interior Region, where the strata are gently tilted off the flanks of the broad domical uplifts (fig. 4). Silurian outcrops are less extensive, however, than those of the adjoining systems, and in places they are truncated, or nearly so, by the systems above. The most prominent band of outcrops encircles the Michigan basin, from northern Ohio, Indiana, and Illinois, through eastern Wisconsin, the Upper Peninsula of Michigan, and southern Ontario (see Geologic Map of Canada), and across the Niagara Gorge in western New York. A large detached area lies southwest of the Wisconsin dome in eastern Iowa and northwestern Illinois. Small remnants are preserved on the flanks of the Nashville and Ozark domes farther south. The New York outcrops bend around the northeastern end of the Allegheny synclinorium into the miogeosynclinal belt of

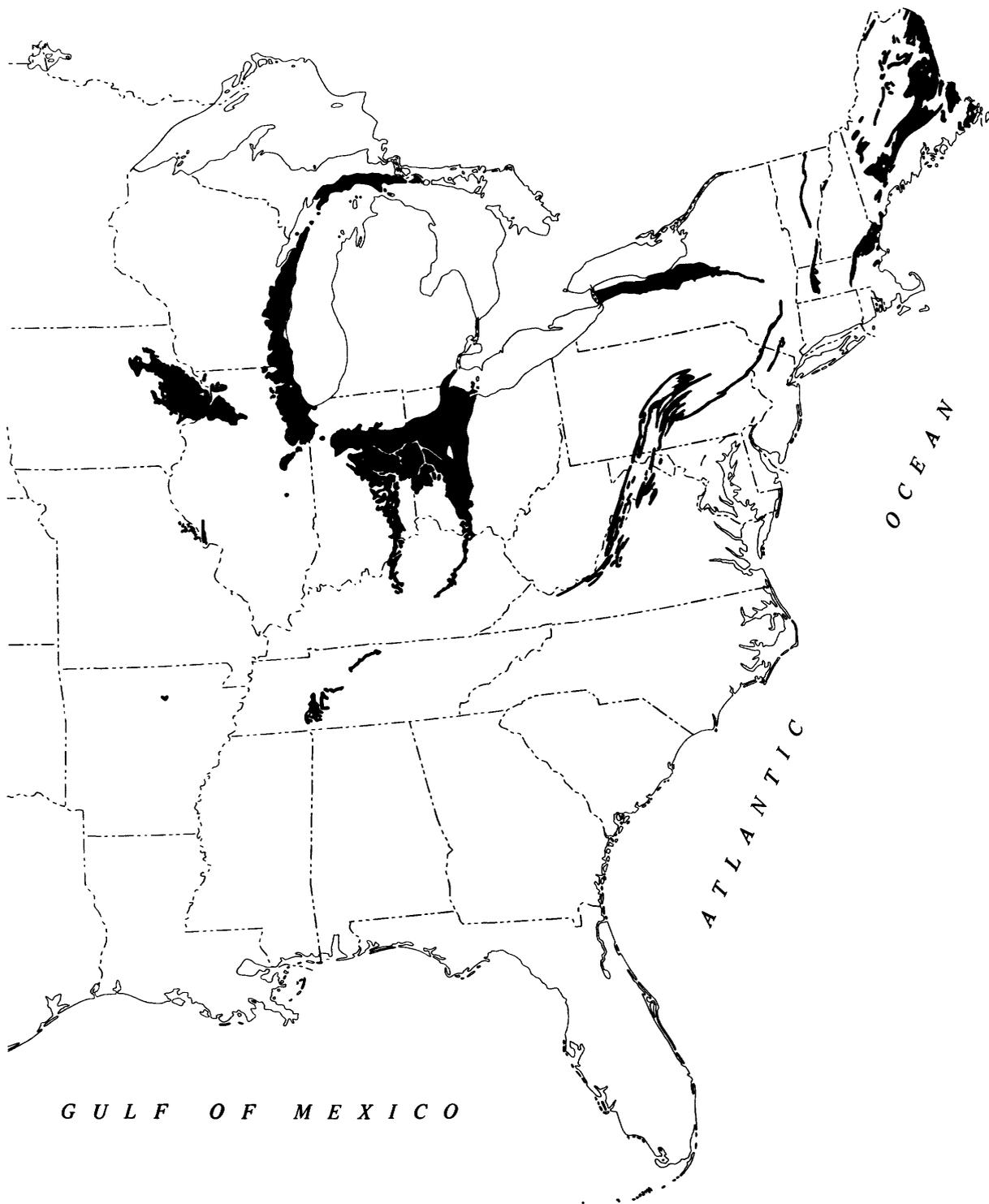


FIGURE 4.—Eastern United States, showing areas mapped as Silurian on Geologic Map of United States. Includes units of marine stratified rocks (S) and their subdivisions (S₁, S₂, S₃), eugeosynclinal deposits (Se), volcanic rocks (Sv), and Silurian and Ordovician eugeosynclinal deposits (SOe).

the Appalachians, where Silurian rocks form numerous bands encircling the folds of the Valley and Ridge province from Pennsylvania into Virginia, but from southern Virginia southwestward the bands become so narrow that they are merged with the Devonian (DS), as in the Ouachita Mountains to the west.

According to North American usage, the Silurian is divided into the Lower Silurian or Alexandrian Series (S₁) (Oswegan or Albion of earlier usage), the Middle Silurian or Niagaran Series (S₂), and the Upper Silurian or Cayugan Series (S₃). This practice conflicts with usage in Great Britain and elsewhere in western Europe, where only a Lower Silurian (Llandovery) and an Upper Silurian (Wenlock and Ludlow) Series are recognized, the boundary between them being in the middle of the North American Middle Silurian (Berry and Boucot, 1970, p. 13–16). Nevertheless, the subdivisions of the Silurian System, where shown on the Geologic Map, follow the conventional North American usage.

The three series of the Silurian are separated on the Geologic Map throughout the broad outcrop areas in the north, but the Middle Silurian (S₂) is the most extensive and accounts for a large part of the outcrop area, partly because of its resistant carbonate formations. The Lower Silurian Series (S₁) is inconsequential except in New York and the Iowa-Illinois area, and the Upper Silurian is only prominent at the surface in northern Indiana and Ohio. It is best developed downdip, in subsurface beneath the Michigan basin and Allegheny synclinorium. The Silurian is not subdivided on the map in the smaller areas in the southern part of the Central Interior, or in the Appalachian miogeosynclinal belt.

Throughout the Central Interior the Silurian sequence is accordant with the Ordovician below and the Devonian above, although separated from them at many places by a hiatus of greater or lesser magnitude. At the Falls of the Ohio near Louisville, for example, Middle Silurian carbonates (Niagaran) are overlain without discordance by Middle Devonian carbonates (Onondaga equivalent), the contact actually being within a single layer. Nevertheless, the Geologic Map indicates a low-angle truncation of the Silurian by the Devonian in Indiana, Illinois, and Iowa.

Eastward along the edge of the folded rocks of the northern Appalachians, a structural unconformity develops at the base of the Silurian sequence, reflecting the Taconian orogeny in this part of the foldbelt. The discordance is prominent west of the Hudson River in southern New York, northern New Jersey, and eastern Pennsylvania but fades out to the south. Northwest-tilted Lower Silurian sandstones and conglomerates (Shawangunk and Tuscarora) overlie highly disturbed

Middle and Upper Ordovician flysch (Normanskill and Martinsburg). A significant outlier of the unconformity occurs at Becraft Mountain east of the Hudson, where Lower Devonian rocks overstep the Silurian and lie directly on deformed and faulted Cambrian and Ordovician rocks of the Taconic allochthon.

Carbonate rocks dominate the cratonic area of the Central Interior. The Niagaran Series in particular, in the middle of the sequence, is a sheet of dolomite that extends westward from New York State to Iowa. One of its stronger layers, the Lockport Dolomite, forms the rimrock of Niagara Falls. The Niagaran carbonates are studded with mound reefs, some of them 400 ft (120 m) thick, which grew on a sea floor of marked relief. In New York, however, the lower part of the Niagaran (Clinton Group) is shaly and contains beds of red iron ore.

Limestones and shales, rather than dolomite, are more prominent in the Lower and Upper Silurian Series, and the latter, or Cayugan, contains large volumes of evaporites, especially rock salt. These have mostly been leached back from the outcrops and are known mainly in subsurface. Cayugan time marked a climax in the sinking of the Michigan basin, and the series is 4,000 ft (1,200 m) or more thick in its center (beneath the cover of younger Paleozoic strata); nearly half of it is salt (Cohee, 1965, p. 217–218). The Cayugan salt deposits have long been exploited commercially, both in Michigan and the Appalachian Region; drilling for salt long preceded drilling for oil in the same areas.

In the Appalachian miogeosyncline the Silurian carbonates give place to clastic deposits, in part nonmarine, related to the Taconian orogeny and its aftermaths. Especially prominent are the ridge-making sandstones of the Lower Silurian, known from place to place as the Shawangunk, Tuscarora, Clinch, and other local terms. In Pennsylvania the Upper Silurian rocks include the Bloomsburg Redbeds, as much as 5,000 ft (1,500 m) thick, which thin westward and intertongue with gray shales and limestones.

EUGEOSYNCLINAL DEPOSITS (Se)

Silurian eugeosynclinal deposits and associated volcanic rocks (Sv) are mapped in the New England States north of Connecticut and Rhode Island. None are known in the Piedmont province of the Central and Southern Appalachians, and probably they do not exist there. As in the adjacent systems, the stratigraphy is plainest to the north and northeast, where the metamorphic grade is low and fossils are relatively abundant—especially in northern and eastern Maine, but also in a peculiar narrow belt of low-grade metamorphism along the Connecticut River in western New Hampshire.

In the northwestern belts flanking the Connecticut Valley synclinorium, the Silurian sequence lies with structural discordance on the Ordovician, and at a few places in northern Maine it is also moderately unconformable below the Devonian. It is thin—generally little more than 1,000 ft (300 m) thick—and includes important bodies of quartz sandstone and carbonate (Shaw Mountain Formation and Northfield Slate on the west flank in Vermont, Clough Quartzite and Fitch Formation on the east flank in New Hampshire, all Middle Silurian). The units in New Hampshire form such narrow outcrop belts and the structure is so complex that they are indicated only in places on the Geologic Map, although they are actually fairly continuous. The Silurian rocks of these belts are more of miogeosynclinal than of eugeosynclinal facies, and their inclusion with "Se" on the Geologic Map is misleading. The deposits represent an interlude in northwestern New England, following the Taconian orogeny, between the eugeosynclinal regimes that dominated Ordovician and Devonian time.

Southeastward into the Merrimack synclinorium in New Hampshire and Maine, the Silurian sequence itself becomes eugeosynclinal and thickens dramatically to more than 15,000 ft (4,600 m), as shown by its wide outcrop bands on the Geologic Map. The Merrimack Group in the south is mainly slates and schists with a few more sandy units and minor volcanic rocks. A band of Silurian slates more than 30 mi (50 km) broad extends northeastward through central Maine, nearly across the State.

Nearer the coast, volcanic rocks (Sv) dominate. They are well displayed in the Eastport area at the eastern tip of Maine, where they are virtually unmetamorphosed and contain fossils at numerous levels that indicate Middle and Late Silurian ages. Farther southwest, metamorphism is greater and fossil control is sparse. Brachiopods and ostracodes in the Ames Knob Formation of the Penobscot Bay area are of Late Silurian age. A few Late Silurian ostracodes have been found in the Newberry Volcanics north of Boston in eastern Massachusetts, and the barren Lynn and Matapan Volcanic Complexes south of it may be of roughly the same age.

DEVONIAN AND SILURIAN

MARINE STRATIFIED ROCKS (DS)

On the Geologic Map, the Devonian and Silurian Systems are combined into a single unit in the miogeosynclinal belt of the Southern Appalachians and in the Ouachita Mountains.

The outcrop belts of both systems become narrow in southwestern Virginia, partly from steepening of the

structure, more from thinning of the sequences. The great wedge of Devonian clastic rocks that is prominent in New York and Pennsylvania thins and becomes inconsequential in Virginia and beyond. In Tennessee the combined thickness of the two systems is about 1,000 ft (300 m), and in Alabama no more than a few hundred feet. In Alabama the units are the Silurian Red Mountain Formation, with red iron ores like those of the Clinton in New York that are exploited commercially at Birmingham, and the Devonian Frog Mountain Sandstone.

Mapped also as undivided Devonian and Silurian in Alabama are the upper rocks of the sequence in the Talladega belt, southeast of the area of miogeosynclinal rocks. These include the persistent Cheaha (= Butting Ram) Sandstone, followed in the south by the Jemison Chert with abundant shelly fossils of Early Devonian age, and farther north by the Erin Slate from which fossil plants of supposed Carboniferous age have been collected. The slates and phyllites in the Talladega sequence beneath the Cheaha Sandstone are indicated on the map as lower Paleozoic (1P) (see below).

In the Ouachita Mountains, the Devonian and Silurian (DS) of the Geologic Map comprise the Blaylock Sandstone with Lower Silurian monograptids; the Missouri Mountain Slate, unfossiliferous but probably also Silurian; and the Arkansas Novaculite. The first two are prominent in the southern outcrop belts but insignificant farther north, whereas the Arkansas is persistent and forms mountain ridges that encircle the older Paleozoic rocks of the core areas. It is a few hundred to a thousand feet (80–300 m) thick and is a condensed sequence with conodonts indicating that it embraces all the Devonian Period and the lower part of the Mississippian (Kinderhookian) as well (Hass, 1951).

EUGEOSYNCLINAL DEPOSITS (DSe)

Many of the source geologic maps in New England designate units by the hybrid term "Devonian and Silurian" or "Devonian or Silurian," indicating either that they contain rocks of both ages (as indicated by fossils or other less direct evidence) or that there is uncertainty as to which system they should be assigned. The Geologic Map of Maine (1967) lists more than 20 such hybrid map units. For the most part, we have arbitrarily assigned such units to one of the two systems on the Geologic Map, on the basis of the preponderance of evidence for one or the other, but this has not been possible in the Merrimack synclinorium that extends from southeastern Maine and New Hampshire to Massachusetts.

The broad band of Silurian eugeosynclinal rocks that

extends across southeastern Maine is separated from the Devonian eugeosynclinal rocks by bands nearly as broad labeled on all the source maps as "Devonian or Silurian," which it would be presumptuous on our part to attempt to classify. Those on the northwestern flank are calcareous silty and sandy rocks (Madrid and Fall Brook Formations) which overlie strata with Upper Silurian (Ludlow) fossils and underlie equivalents of the Devonian Seboomook Formation; those on the southeastern flank (Vassalboro and Berwick Formations) similarly overlie fossiliferous Upper Silurian but lack Devonian rocks at the top (Osberg and others, 1968; Ludlum and Griffin, 1974). The Geologic Map also extends the southeastern belt of "Devonian or Silurian" to the better dated rocks near Penobscot Bay to include rocks that were poorly understood at the time of compilation. Surveys now available indicate that this area is more heterogeneous than realized and includes not only Devonian and Silurian but also older Paleozoic and possibly even Precambrian rocks (Osberg, 1974).

On the west flank of the Merrimack synclinorium next to the Bronson Hill anticlinorium, the Geologic Map indicates a broad band of "Devonian or Silurian" in southern New Hampshire, Massachusetts, and Connecticut. On the Geologic Map of New Hampshire (1955), the part in that State was mapped as Devonian Littleton Formation, but there and in Massachusetts later work has indicated the existence of complex nappe structures that involve not only the Devonian but rocks as old as the Ordovician Partridge Formation (Thompson and others, 1968). Not all these complexities are yet resolved, and the noncommittal designation of DSe was recommended by geologists of the Survey who are working in New England. The eastern boundary of the area, as shown on the Geologic Map, is unsatisfactory and probably does not express the true relations.

DEVONIAN

The Devonian System is represented on the Geologic Map of the United States by marine stratified rocks (D), divided in part into Lower, Middle, and Upper Devonian Series (D₁, D₂, D₃); by Middle and Upper Devonian continental deposits (D_{2c}, D_{3c}); and by eugeosynclinal deposits (De), with associated volcanic rocks (Dv). The Devonian, like the Silurian, is shown separately only in the northeastern third of the country; in the Southern Appalachians and the Ouachita Mountains it is combined with the Silurian (DS), and from the Rocky Mountains westward it is combined with the other lower Paleozoic systems (1P, 1Pe).

MARINE STRATIFIED ROCKS (D)

As with the systems below and above, the Devonian

is most extensively exposed in the cratonic area of the Central Interior Region (fig. 5), where the strata are gently tilted on the flanks of the broad domes and basins. The most prominent area of outcrop is that in southwestern New York and adjacent Pennsylvania and Ohio, where the strata dip gently southwestward into the Allegheny synclinorium. It displays the classic Devonian sequence, known since the early days of the New York Survey a century and a half ago, to which much of the system in the rest of the country has frequently been compared. Somewhat narrower bands of outcrops encircle the Cincinnati dome and Michigan basin in Ohio, Indiana, and Michigan, and a large outlying area of southwest-tilted Devonian strata occurs in Iowa and adjacent Minnesota and Illinois. The New York outcrops bend around the northeastern end of the Allegheny synclinorium into the miogeosynclinal belt of the Appalachians, where the Devonian rocks form numerous bands among the folds of the Valley and Ridge province through Pennsylvania into Virginia. Beyond Virginia they thin to such an extent that they are combined with the Silurian (DS).

According to North American usage, the Devonian is divided into the Lower Devonian Series (Helderberg and Oriskany) (D₁), the Middle Devonian Series (Onondaga, Hamilton, and Tully) (D₂), and the Upper Devonian Series (consisting of the remainder of the system) (D₃). The resulting subdivisions are quite unequal, the Lower Devonian being thin and inconstant and the Upper Devonian very thick—as is well illustrated on the Geologic Map by the relative widths of the three series in New York. As a substitute, five named series have been proposed: Ulsterian, Erian, Senecan, Chautauquan, and Bradfordian, the last three in the Upper Devonian (Cooper and others, 1942, p. 1732). In addition, the European stage names (Gedinnian, Coblenzian, Eifelian, Gevetian, Frasnian, and Famennian) have come into increasing use in North America.

The three series of the Devonian System are differentiated on the Geologic map throughout the broad areas in the north, which for the most part consist about equally of Middle and Upper Devonian rocks. The Lower Devonian Series appears only as a narrow band in New York State; where present elsewhere, it is combined with the Middle Devonian. The Devonian is not subdivided on the map in the smaller outcrop areas in the Central Interior, nor in the Appalachian miogeosynclinal belt.

The Devonian sequence of the eastern outcrops in New York and Pennsylvania is 12,000 to 15,000 ft (3,600–4,500 m) thick, forming the apex of a great clastic wedge of Middle and Upper Devonian deposits, partly continental (see below), that is frequently referred to as the "Catskill delta." The wedge is a product

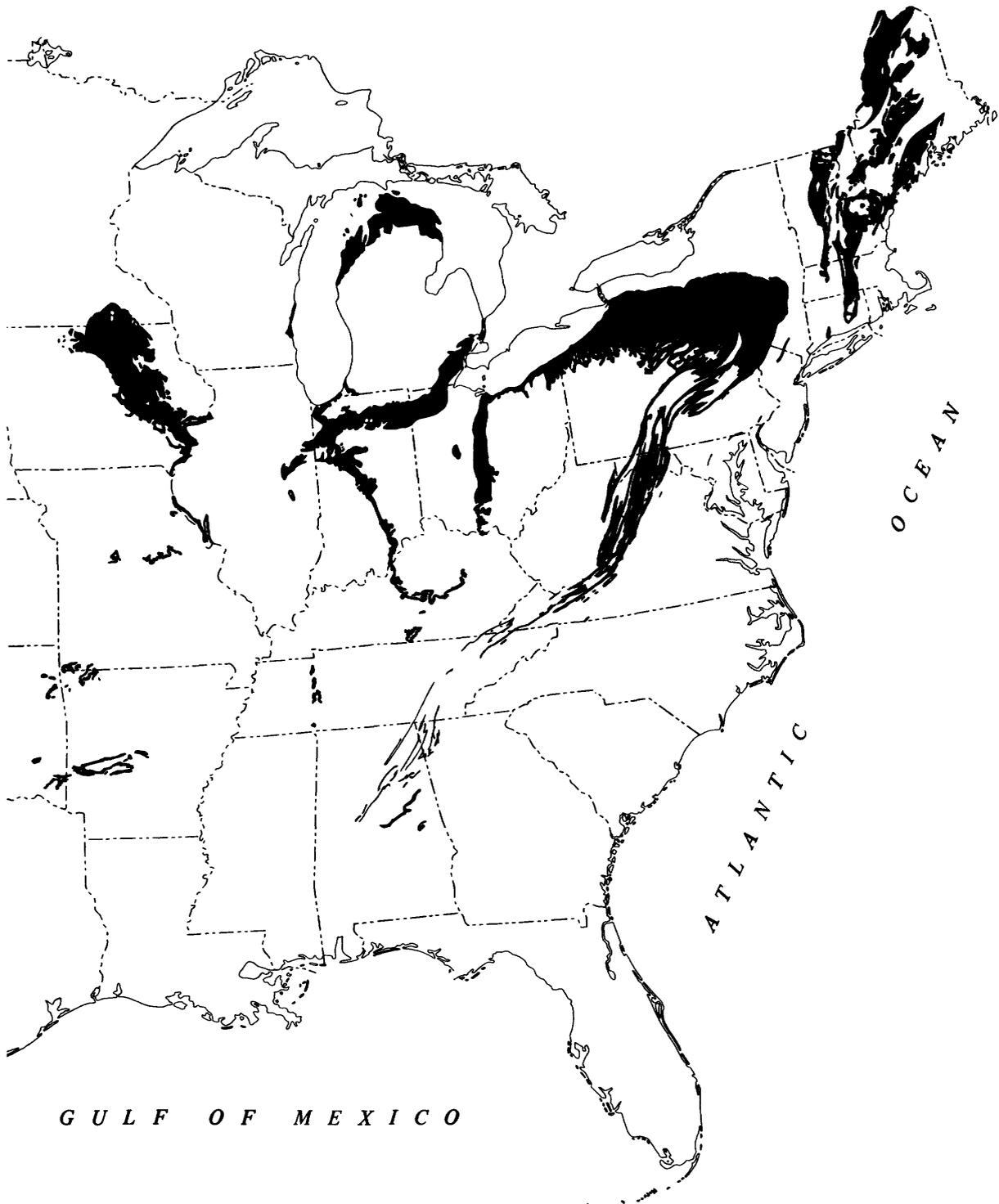


FIGURE 5.—Eastern United States, showing areas mapped as Devonian on Geologic Map of United States. Includes units of marine stratified rocks (D) and their subdivisions (D1, D2, D3), Devonian and Silurian marine stratified rocks (DS), continental deposits (D2c, D3c), eugeosynclinal deposits (De), volcanic rocks (Dv), Devonian and Silurian eugeosynclinal deposits (DSe), and volcanic rocks (DSv).

of the Acadian orogeny that was in progress in the Appalachian foldbelt to the east, and it thins westward into the Central Interior Region, as well as southwestward along the strike in the Appalachian miogeosynclinal belt.

The Lower Devonian strata and the Onondaga Limestone precede the development of the clastic wedge and consist of thin persistent shale and limestone units, as well as one prominent sandstone layer, the Oriskany. The Onondaga and its equivalents extend far westward into the Central Interior, for example, to the Falls of the Ohio at Louisville, Ky., mentioned earlier.

In New York, the Middle and Upper Devonian coarse clastic rocks intertongue westward with finer grained sandstones, gray shales, and thin limestones; these intertongue in turn with black shales (Cooper, 1933; Chadwick, 1935), the transitions in each successive part being displaced a little farther west. West of New York the Middle and Upper Devonian sequences are no more than a few thousand feet (300–600 m) thick. There are important limestone units in the Middle Devonian, with coral and stromatoporoid reefs and banks, but the Upper Devonian is shaly as far west as the Mississippi River.

Upper Devonian black shales with various spans of age are extensive in the Midwestern States, including such units as the Ohio, New Albany, and Antrim Shales. They are followed in places by similar shales of Early Mississippian (Kinderhookian) age, creating problems in placing the Devonian-Mississippian boundary on the Geologic Map. This is the case, for example, in the heavily drift covered border region between Indiana and Michigan, underlain by the Antrim, New Albany, Ellsworth, Sunbury, and Coldwater Shales, the middle three being indicated on the State Maps as "Devonian and Mississippian"; on the Geologic Map the systemic boundary is arbitrarily located between the New Albany and the Ellsworth.

South of Virginia the sole representative of the black shales is the thin very persistent Chattanooga Shale (included in DS on the Geologic Map), mostly Late Devonian but including Early Mississippian beds in places, that is notable not only for its conodont fauna (Hass, 1956) but also for radiometric dating of its uraniumiferous shales at 350 m.y. It lies with a hiatus on earlier Devonian rocks, which it oversteps to rest on strata as old as Ordovician, producing a low-angle regional unconformity traceable as far west as Oklahoma.

CONTINENTAL DEPOSITS (D_{2c}, D_{3c})

As indicated above, the proximal part of the Middle and Upper Devonian clastic wedge in New York and

Pennsylvania is formed of continental deposits—conglomerates, coarse sandstones, and redbeds that include a fossil forest at Gilboa, N.Y., of late Middle Devonian (Tully) age. The continental deposits project in the heights of the plateaulike Catskill Mountains that overlook the Hudson Valley. The extent of the continental deposits indicated on the Geologic Map is based on the Geologic Maps of New York and Pennsylvania.

Small patches of little-deformed red continental deposits, in part plant bearing, also occur within the Appalachian foldbelt in eastern Maine, which are younger than the Acadian orogeny and lie on upended Devonian and earlier Paleozoic eugeosynclinal rocks. The Mapleton Sandstone of Aroostook County is late Middle Devonian, and the Perry Formation of the Eastport district at the eastern tip of Maine is Late Devonian; the ages of other occurrences are less certain. For convenience, all are grouped as Middle Devonian (D_{2c}) on the Geologic Map.

EUGEOSYNCLINAL DEPOSITS (De)

Devonian eugeosynclinal deposits and associated volcanic rocks (Dv) are prominent in New England, but none are known in the Piedmont province of the Central and Southern Appalachians. All the eugeosynclinal Devonian rocks in New England are Lower Devonian (or no younger than low Middle Devonian)—in contrast to the scanty Lower Devonian Series in the miogeosyncline and craton to the west—and mark the final climax of eugeosynclinal subsidence and sedimentation prior to the Acadian orogeny. Devonian deposits, well dated by fossils, form broad outcrop belts in Vermont, New Hampshire, and Maine; narrower more metamorphosed extensions have been traced into Massachusetts and Connecticut.

Devonian phyllites and schists form a belt 25 mi (40 km) wide in the trough of the Connecticut Valley synclinorium in eastern Vermont and are as much as 15,000 to 20,000 ft (4,500–6,000 m) thick. The western part (Waits River Formation) is calcareous and the eastern part (Gile Mountain Formation) is quartzose; they have complex mutual relations, partly from intergradation, partly from major nappe structures. Metavolcanic rocks are rare, except for an amphibolite layer in the eastern part and fossils are rather sparse. Equivalents extend southward in a narrower belt into Massachusetts, where they include the long-known fossil locality at Bernardston. A small patch (Wepawaug Schist=upper part of Orange Phyllite of earlier usage) emerges from beneath the Triassic cover west of New Haven, Conn. (Fritts, 1962).

The northeastern part of the Connecticut Valley synclinorium in northern Maine is dominated by the Seboomook Formation, a mass of deep-water shaly and

sandy turbidites as much as 20,000 ft (6,000 m) thick (Boucot, 1961, p. 169-171). However, a shoal-water belt extending from Moosehead Lake northeastward for 90 mi (140 km) to north of Mount Katahdin received sandy deposits (Tarratine and Matagamon Formations). Early Devonian (Oriskany and early Onondaga) fossils are abundant in the shoal-water deposits and sparse in the deep-water deposits. Lying on the shoal-water deposits at Mount Kineo, Traveler Mountain, and elsewhere are thick masses of rhyolitic volcanic rocks (Dv), probably erupted from calderas in an island arc (Rankin, 1968). They are succeeded by several thousand feet (300-600 m) of additional sediments—the shallow-water Tomhegan Formation at Moosehead Lake and the brackish-water or terrestrial Trout Valley Formation at Traveler Mountain. The former contains Oriskany shelly fossils, the latter fossil plants of early Middle Devonian age. The Trout Valley Formation is unmetamorphosed and little deformed and is either a late orogenic or a postorogenic deposit.

In the Bronson Hill anticlinorium of New Hampshire, east of the Connecticut Valley synclinorium, the Silurian is overlain by the Littleton Formation of shaly and sandy rocks with a volcanic member near the middle (mainly tuffs and breccias); it has been variably metamorphosed to phyllite or to garnet and sillimanite schists and gneisses (Billings, 1956, p. 27-35). Lower Devonian (Oriskany) fossils are well preserved in the low-grade belt along the Connecticut River, and a few have been recovered even in the high-grade rocks farther east. The Littleton is about 4,500 ft (1,400 m) thick in the Bronson Hill anticlinorium, but like the preceding Silurian it thickens eastward into the Merrimack synclinorium to 16,000 ft (4,900 m).

The Devonian and Silurian rocks of the Merrimack synclinorium in New Hampshire continue southward into east-central Massachusetts, but relations here have been clouded by the occurrence of Carboniferous (Pennsylvanian?) plants at the "coal mine" near Worcester, and so for many years the whole complex of deposits was assigned to the Carboniferous system—as it was on the Geologic Map of the United States of 1932, following Emerson (1917). The main body of the rocks is, however, lithically very different from the authentic Pennsylvanian of the Narragansett and Boston basins to the southeast, and it was involved in the mid-Paleozoic (Acadian) deformation. Present judgment is that the rocks at the "coal mine" are merely a remnant of a younger formation enclosed tectonically in much older rocks. On the Geologic Map, Pennsylvanian (P) is marked in a small patch at the fossil locality, and the surrounding rocks are classed as Silurian and Devonian (Se, De).

LOWER PALEOZOIC

From the Rocky Mountains westward, the Cambrian, Ordovician, Silurian, and Devonian Systems form such small outcrops, either singly or together, that they are combined on the Geologic Map of the United States into a unit of lower Paleozoic, with a distinction between marine stratified rocks (1P) and eugeosynclinal deposits (1Pe). In a few areas the Cambrian sequence (C) forms outcrops sufficiently extensive for representation; elsewhere it is merged with the other systems. The same designation is also used for some small outcrops of lower Paleozoic rocks farther east in the United States, as explained below.

MARINE STRATIFIED ROCKS (1P)

The lower Paleozoic marine stratified rocks are of several different kinds—cratonic deposits, miogeosynclinal deposits, and miscellaneous rocks of outlying areas—which it is appropriate to describe separately.

CRATONIC DEPOSITS

Lower Paleozoic cratonic deposits similar to those in the Central Interior Region extend across the Central and Southern Rocky Mountains, the Colorado Plateau, and the Basin and Range Province of New Mexico and Arizona; there they are exposed in narrow bands of tilted strata along the edges of the uplifts of Precambrian rocks (fig. 6). The Cambrian is shown separately in Arizona, but in some parts of the Basin and Range Province all the lower Paleozoic is missing.

The lower Paleozoic cratonic deposits are no more than a few hundred or few thousand feet (60-600 m) thick in any of the outcrops, and each system has its own pattern of distribution and thickness independent of the others, reflecting in part the shifting through time of the epicontinental seas (fig. 7). Sequences at any locality are thus incomplete, lacking one or more systems or parts of systems. Details of distribution and thickness of the systems in outcrop and subsurface are illustrated in the "Geologic Atlas of the Rocky Mountain Region" (Mallory, 1972), to which the reader is referred. Especially notable is the complete absence of Silurian rocks from any outcrop area except in southern New Mexico, although its former presence in places is suggested by remnants preserved in diatremes in northern Colorado.

Equally interesting are the areas where the lower Paleozoic rocks are missing entirely and upper Paleozoic or lower Mesozoic rocks lie directly on Precambrian. Some of these areas, such as the Front Range in Colorado and Wyoming and the Uncompahgre Plateau in western Colorado, were the sites of geanticlines that were raised in later Paleozoic time,

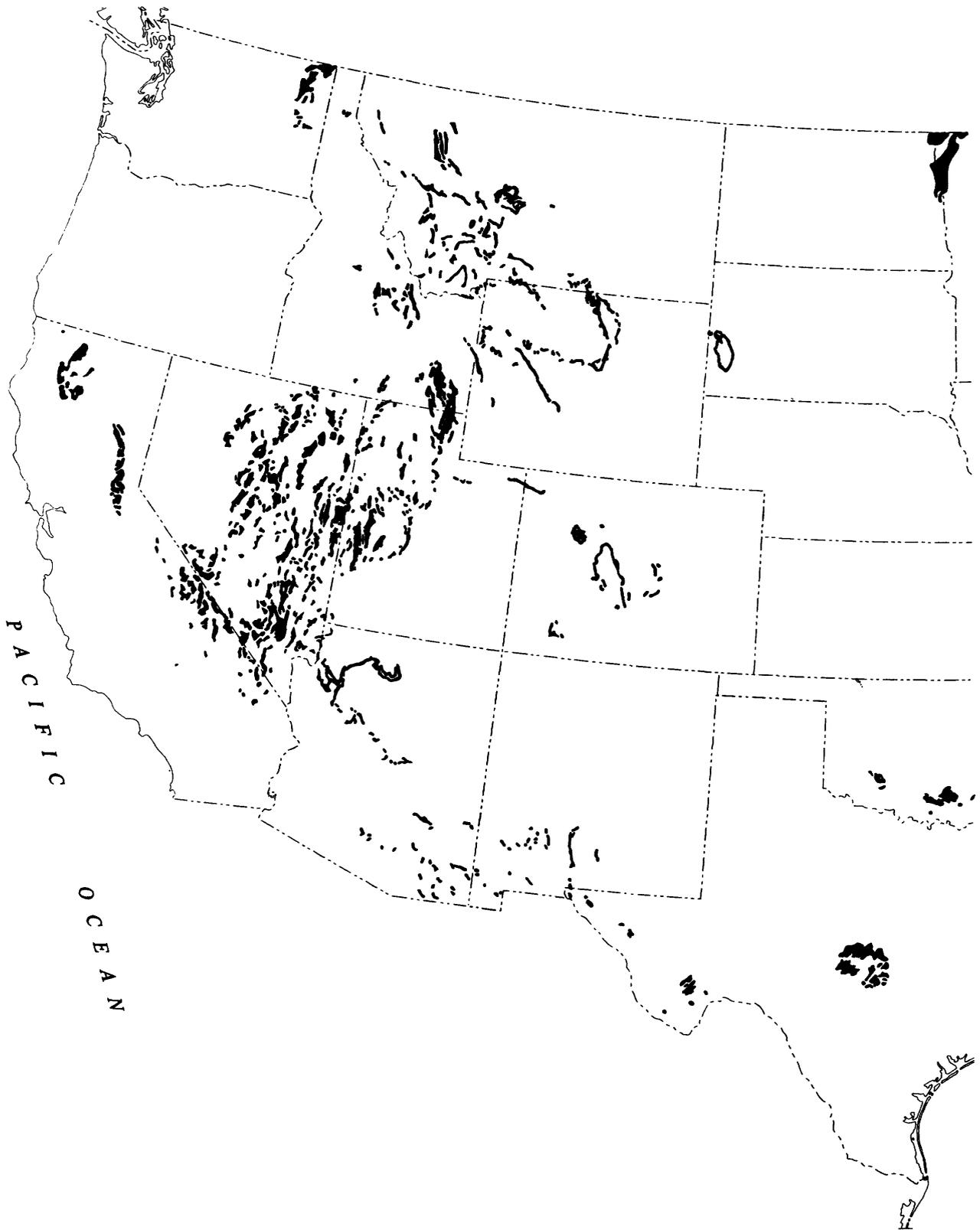


FIGURE 6.—Western United States, showing areas mapped as lower Paleozoic on Geologic Map of United States. Includes units of marine stratified rocks (1P), eugeosynclinal deposits (1Pe), Cambrian (C), and Lower Ordovician (O1).



FIGURE 7.—Eastern part of Cordilleran Region, showing surface and subsurface extent of the different systems grouped as lower Paleozoic on Geologic Map of United States: A—Cambrian (lines L, M, and U indicate maximum extent of Lower, Middle, and Upper Cambrian Series), B—Ordovician, C—Silurian, D—Devonian. Compiled from Geologic Atlas of Rocky Mountain Region (Mallory, 1972) and other sources.

when older deposits, if they had ever existed, were eroded. Other areas, such as the block ranges of northern New Mexico, are parts of the "Transcontinental arch," a paleotectonic feature that extended south-westward from the Lake Superior Region, upon which many of the Paleozoic systems either never deposited or were laid down so thinly that they were removed later. Relations are well illustrated in the New Mexico ranges, where representatives of all the lower Paleozoic systems occur in the south but with each one thinning and wedging out northward toward the site of the arch until none remain.

Westward from southern New Mexico, only Cambrian rocks and a thin Devonian formation (Martin Limestone) persist into Arizona. Here, it is appropriate on the Geologic Map to represent the Cambrian (C) but to merge the Devonian with the Mississippian and Pennsylvanian into a unit of upper Paleozoic (uP).

MIOGEOSYNCLINAL DEPOSITS

The miogeosynclinal lower Paleozoic rocks form all or large parts of many of the ranges in the Northern Rocky Mountains and the eastern Great Basin. Here, the Cambrian System can be separated at many places on the Geologic Map.

The miogeosynclinal deposits do not differ in either lithology or origin from the cratonic deposits, but they are greatly thicker and have a more complete sequence. In Utah, the change from craton to miogeosyncline takes place near the present western edge of the Colorado Plateau along the "Wasatch line"—a tectonic boundary with ancient antecedents. West of it in the Great Basin, Lower Cambrian strata wedge in at the base of the sequence, and all the succeeding lower Paleozoic deposits thicken; Silurian rocks, so notably missing from the craton to the east, make their appearance. Contrasts between the two lower Paleozoic sequences have been further emphasized during the Cretaceous Sevier orogeny, when the two were telescoped along great thrusts along the "line."

In the Great Basin of western Utah and eastern Nevada, Middle Cambrian through Devonian sequences are characteristically 10,000 to 15,000 ft (3,000–4,500 m) thick and overlie 3,000 ft (900 m) or more of Lower Cambrian clastic deposits. The long-known sequence at Eureka, east-central Nevada, is 14,500 ft (4,300 m) thick and is composed of 60 percent limestone, 30 percent dolomite, 8 percent shale, and 2 percent quartzite (Nolan and others, 1956). A notable sandy unit above the basal clastics is the Middle Ordovician Eureka Quartzite (= Swan Peak Quartzite) about 300 ft (100 m) thick, which spreads across most of the eastern half of the Great Basin, like the nearly

contemporaneous Saint Peter Sandstone of the Central Interior, and like the Saint Peter is derived from areas of crystalline rocks in the craton. Not only are the Cambrian and Lower Ordovician rocks of carbonate facies, as in the Appalachian miogeosyncline, but also so are the younger lower Paleozoic systems; the strata above the Eureka Quartzite in the Eureka district (Upper Ordovician, Silurian, and Devonian) are about 6,000 ft (1,000 m) of limestone and dolomite.

Some of the lower Paleozoic miogeosynclinal strata are involved in a highly metamorphosed plastically deformed infrastructure (C and lP, with metamorphic overprint) which emerges in windows from beneath the less altered Paleozoic rocks in the Ruby Range, north-eastern Nevada, and in tectonically similar situations to the east and north.

Mapped with the lower Paleozoic miogeosynclinal rocks is the so-called "transitional assemblage" of formations (C and lP) which are tectonically entangled with rocks of the eugeosynclinal or "western assemblage" east and northeast of Winnemucca, north-central Nevada (Roberts and others, 1958, p. 2817), but which have features not entirely like either the miogeosynclinal or the eugeosynclinal deposits. They include a thick quartzite like the Lower Cambrian clastic deposits farther east, various overlying graptolite shales, and the remarkable Upper Cambrian Harmony Formation, an arkosic turbidite of unknown provenance which is interleaved tectonically with quite different Paleozoic and Mesozoic rocks in many ranges.

ROCKS OF OUTLYING AREAS

Besides the cratonic and miogeosynclinal rocks of the Cordilleran Region, some rocks in small areas farther east, in Texas, Oklahoma, and the Southern Appalachians are mapped as undivided lower Paleozoic.

The Marathon region of western Texas is a small-scale replica of the Ouachita Mountains foldbelt, and its Cambrian, Ordovician, and Devonian rocks are broadly similar to the lower Paleozoic of the Ouachitas. They are exposed in several anticlinoria which are too small on the scale of the map to permit subdivision.

In the Arbuckle and Wichita Mountains of southern Oklahoma, the Upper Cambrian Reagan Sandstone and overlying carbonates are separately mapped (C), but the succeeding lower Paleozoic sequence is not subdivided (lP). Much of the latter is Ordovician, which includes the very thick carbonates of the Lower Ordovician Arbuckle Group, but thin Silurian and Devonian units (Hunton Group and Woodford Chert) occur at the top.

The designation lower Paleozoic (lP) is used for rocks in a few outcrop belts in the Piedmont province of

the Southern Appalachians; their precise ages are uncertain, but they appear to be younger than the rocks adjacent to them. Their occurrence is as follows:

(1) Slates and phyllites in the Talladega belt, Alabama, below the Cheaha Sandstone and associated fossiliferous rocks (DS); they may be Ordovician, but both older and younger ages have been claimed.

(2) The Wedowee Formation and Ashland Schist in the next belt to the southeast, composed of rocks like those in the lower part of the Talladega sequence but more metamorphosed and more involved with plutonic rocks.

(3) Rocks of the Wacoochee (= Pine Mountain) belt of the southern Piedmont in Georgia and Alabama (Hollis Quartzite, Chewacla Marble, and Manchester Schist), which lie with apparent unconformity on orthogneisses (Ygn) that have yielded 1,000-m.y. radiometric dates.

(4) Rocks of the Murphy Marble Belt in northeastern Georgia and southwestern North Carolina. They overlie and are synclinally downfolded into the Ocoee Supergroup (Z) and include the Murphy Marble near the top. The marble has been correlated with the Lower Cambrian Shady Dolomite on physical resemblance, and a few poorly preserved Paleozoic fossils have been recovered from it.

(5) Low-grade schists of the Chauga belt on the southeastern side of the Brevard fault zone in northwestern North Carolina.

(6) Rocks of the Kings Mountain belt on the South Carolina-North Carolina border east of the Brevard fault zone, which include distinctive units of schist and quartzite, and the Gaffney Marble.

EUGEOSYNCLINAL DEPOSITS (1P_e)

Lower Paleozoic eugeosynclinal deposits occur mostly in Nevada and California, the only exceptions shown on the Geologic Map being a few small areas in south-central Idaho. In contrast to the carbonate-quartzite facies of the miogeosynclinal belt to the east, they are a facies of clastics, cherts, and volcanics. All of them are either continental margin or "off the continent" deposits, but they probably formed in diverse environments, which are difficult to reconstruct because of the wide separation of the different groups of exposures.

The eugeosynclinal rocks in Nevada crop out in the ranges of the Great Basin in a belt 80 mi (130 km) wide that extends south-southwest across the center of the State from the Idaho border to the California border. For more than half this breadth, the eugeosynclinal rocks are allochthonous on the contemporaneous miogeosynclinal rocks along a major surface of movement, the Roberts thrust, which formed during the Ant-

ler orogeny of late Devonian and early Mississippian time. The miogeosynclinal rocks appear as windows in the different ranges, partly or wholly surrounded by the overlying eugeosynclinal rocks. The lower Paleozoic sequence is overlain by postorogenic Mississippian and Pennsylvanian deposits (Diamond Peak Formation, Battle Formation, and others).

The lower Paleozoic eugeosynclinal sequence in Nevada is probably as much as 50,000 ft (15,000 m) thick, although not all of it is preserved in any one area (Roberts and others, 1958, p. 2816-2817). On the average, shale constitutes 20 to 40 percent; sandstone, graywacke, and quartzite 10 to 30 percent; and volcanic rocks from a few percent to 30 percent. The volcanic rocks are andesitic and basaltic pillow lavas and associated pyroclastics. The most extensive component is of Ordovician age (the shaly Vinini Formation and the equivalent sandy Valmy Formation farther northwest). Rocks of other ages occur only in smaller areas. The Cambrian (Scott Canyon Formation) is represented only in a small outcrop in the south part of Battle Mountain. The Silurian and Devonian rocks (Elder Sandstone and Slaven Chert) are typically developed in the northern Shoshone Range, although they occur sporadically elsewhere. Graptolites are common in the Ordovician and Silurian and are the chief means of zonation and correlation; other fossils are more sparse, both here and in the lower and higher beds.

In the Sierra Nevada of eastern California, lower Paleozoic eugeosynclinal rocks occur both east and west of the Jurassic and Cretaceous granitic rocks of the Sierra Nevada batholith in the core of the range. Those on the eastern side, west and northwest of Owens Valley, are preserved only in roof pendants up to 19,000 ft (5,800 m) thick and are mostly Ordovician (Rinehart and others, 1959, p. 941-944). Those on the west side extend southward along the foothills for more than 100 mi (160 km) from Taylorsville past Placerville and are collectively termed the Shoo Fly Formation (although other names have been given to different parts in the past) (Clark and others, 1962; McMath, 1966, p. 178-179). Fossils of Silurian age have been obtained in one area near Taylorsville; other parts are barren but might include Ordovician as well as Silurian rocks. The Shoo Fly attains a thickness as great as 50,000 ft (16,000 m), with no base visible, and consists of weakly metamorphosed phyllite and minor chert, siltstone, and quartzose sandstone, and some tuff and greenstone. It is overlain unconformably toward the northeast by the dacitic volcanics of the Sierra Buttes Formation which contain Devonian ammonoids in quartzite lenses (Anderson and others, 1974). On the west it is adjoined by the Calaveras Formation which

is generally considered to be upper Paleozoic, but the contact is mostly faulted.

In northern California, lower Paleozoic eugeosynclinal rocks occur in the eastern subprovince of the Klamath Mountains, where they are so entangled with ultramafic rocks and Jurassic granitic plutons that only fragments are preserved in any area and no complete sequence is known. In the north, west of Mount Shasta, are the Duzel and Gazelle Formations (Hotz, 1971, p. 7–8) of shale, volcanic graywacke, chert, and lenticular limestone, the one in thrust contact with the other. Shelly fossils (corals, brachiopods, and trilobites) in the limestone lenses indicate that the Duzel is Late Ordovician(?) and the Gazelle is Silurian. No younger Paleozoic rocks are known in the area. Farther south, in the Redding area, is a mass of Devonian volcanics—the Copley Greenstone that includes andesitic pillow lavas, and the local overlying body of Balaklala Rhyolite. They are capped by cherty shales and local limestone banks of the Kennett Formation with Middle Devonian fossils, shoal water deposits that probably accumulated on the crest of a volcanic island arc. The Devonian rocks are overlain by the Mississippian Bragdon Formation, but the contact is seemingly tectonic.

The central metamorphic belt of the Klamath Mountains is a thrust slice west of and tectonically beneath the rocks of the eastern subprovince. It is formed of Salmon Hornblende Schist and Abrams Mica Schist, which have yielded K/Ar radiometric ages of 270–329 m.y. and Rb/Sr ages of 380 m.y., indicating that the original rocks are Devonian and older and had a protracted mid-Paleozoic metamorphic history (Hotz, 1971, p. 10–11). They might be metamorphic equivalents of some of the lower Paleozoic eugeosynclinal rocks farther east, and they are indicated on the Geologic Map as $l\mathcal{P}e$, with metamorphic overprint.

MISSISSIPPIAN

The Mississippian System (M) is portrayed on the Geologic Map of the United States in the eastern two-thirds of the country; from the Rocky Mountains westward it is merged with the other upper Paleozoic systems into a single unit ($u\mathcal{P}$, $u\mathcal{P}e$). Within the region where it is mapped, the Mississippian is classed as marine stratified rocks; some continental deposits occur in the northeastern part of the Central Appalachians but are not separated. No eugeosynclinal deposits are distinguished; they are missing in the Appalachian Region, where eugeosynclinal conditions were terminated by the Devonian Acadian orogeny. Eugeosynclinal deposits are known only in the extreme western part of the United States, where those of

Mississippian age are merged with the rest of the upper Paleozoic ($u\mathcal{P}e$).

The Mississippian System is essentially the same as the Lower Carboniferous of Europe, and the differences are not fundamental; the top of the Lower Carboniferous is placed between the Visean and Namurian Stages, at a level within the American Chesterian Series (Weller and others, 1948, p. 107–109). The U.S. Geological Survey defers to European usage by designating the Mississippian and Pennsylvanian as “the Carboniferous Systems.” The American Mississippian is divided into the Kinderhookian, Osagean, Meramecian, and Chesterian Series, the first two being combined on the Geologic Map as M_1 , the other two being labeled M_2 and M_3 . The first two have also been called Lower Mississippian and the second two Upper Mississippian, but these are not useful for purposes of the Geologic Map.

As with the other Paleozoic systems, the Mississippian is most extensively exposed in the cratonic area of the Central Interior Region, where it forms broad bands of gently tilted strata between the crests of the domes and the depths of the basins (fig. 8). From the type region along the upper Mississippi River in Iowa and Illinois, outcrops are nearly continuous southwestward around the Ozark dome, southeastward around the Illinois basin around the Nashville and Cincinnati domes, and on the flank of the Allegheny synclinorium. A large detached area in the lower peninsula of Michigan surrounds the Michigan basin. Where the outcrop belts are sufficiently wide, the system is divided into the three parts (M_1 , M_2 , M_3).

Mississippian rocks also form narrow outcrop bands throughout the miogeosynclinal belt of the Central and Southern Appalachians and occur farther southwest in the deformed areas of the Ouachita and Arbuckle Mountains of Arkansas and Oklahoma and the Marathon region of western Texas.

The Mississippian strata are generally conformable with the Devonian; the black shales in the upper part of the latter are followed by black shales in the Kinderhookian series. Throughout much of the Interior Region, Mississippian rocks are unconformable beneath the Pennsylvanian, the discordance being most prominent toward the north, where the Chesterian series is missing at the top of the Mississippian and the Morrowan and Atokan series are missing at the base of the Pennsylvanian. In Iowa and northern Illinois, the Pennsylvanian sequence bevels the Mississippian at a low angle, to the west lying on different subdivisions of the Mississippian sequence and farther east on rocks of earlier ages down to the Ordovician.

The Mississippian sequence is 6,000 ft (1,800 m) or

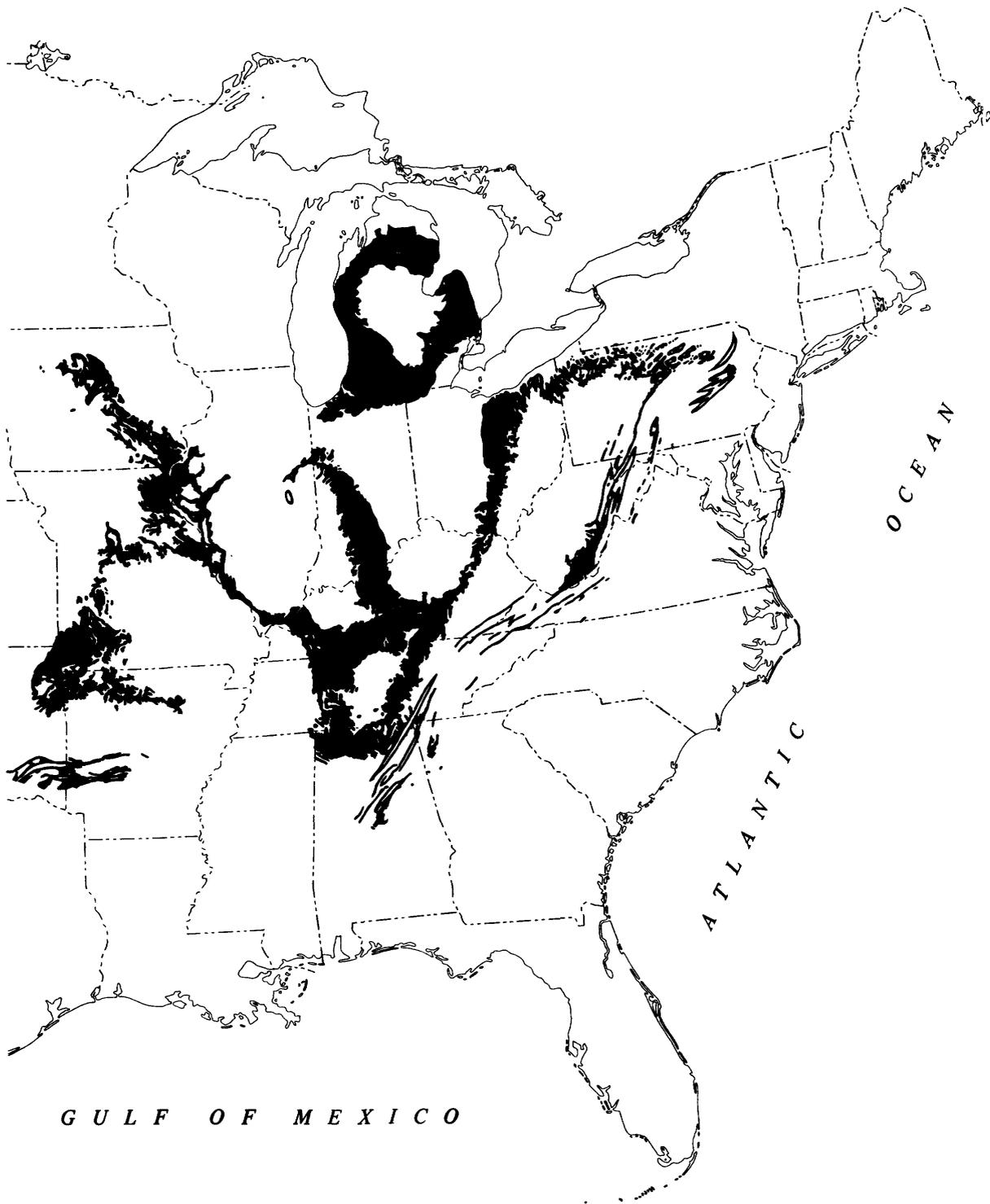


FIGURE 8.—Eastern United States, showing areas mapped as Mississippian on Geologic Map of United States. Includes units of marine stratified rocks (M) and their subdivisions (M1, M2, M3).

more thick in the Appalachian miogeosyncline. To the northeast, in eastern Pennsylvania, it is largely continental (Pocono and Mauch Chunk Formations), with a few thin coal beds in the lower part. Southwestward along the strike it is marine, with much limestone in the middle (in the Meramecian series) and with shales and sandstones below and above. In Alabama, the lower part of the Chesterian series is the Floyd Shale, which oversteps eastward in the Valley and Ridge province onto rocks as old as Early Ordovician. The upper part is the Parkwood Formation, a sandy unit which may extend conformably upward into the basal Pennsylvanian.

Westward into the Central Interior, the Mississippian rocks thin to little more than a few thousand feet (300–600 m) and are mainly limestone. Oolitic limestones in the Meramecian series near Bedford, Ind., are extensively quarried for building stone. The Kinderhookian and Osageian limestones of Iowa and Illinois are famous for their crinoids. Farther south, the Osageian carbonates are siliceous in such units as the Fort Payne Chert near the Nashville dome and the Boone Chert on the south flank of the Ozark dome. The Chesterian Series at the top is more heterogeneous than the rest, with much sandstone and many little units of shale and limestone.

Near the common corners of Missouri, Oklahoma, and Arkansas, there are discrepancies between the State Maps in representation of the subdivisions of the Mississippian System. In southwestern Missouri the map shows Osageian (cherty limestones) (M_1), Meramecian (limestones) (M_2), but no Chesterian (M_3). In northeastern Oklahoma the map shows Boone Chert (presumably Osageian), followed by Chesterian rocks; much the same units continue eastward into Arkansas. The Chesterian series wedges out northeastward near the northeastern corner of Oklahoma; the Meramecian of Missouri must continue southwestward into the upper part of the Boone Chert, but its extent is uncertain. On the Geologic Map, the Meramecian series is shown as wedging out southwestward in Oklahoma, beyond which Osageian rocks (M_1) are shown in contact with Chesterian (M_3); rocks of Meramecian age may be present also but are not represented on the Geologic Map.

A very different facies of the Mississippian sequence from those considered so far occurs in the foldbelt of the Ouachita Mountains in Arkansas and Oklahoma and in its outlier in the Marathon region of western Texas. Here, novaculite is succeeded abruptly by a great flysch sequence. The novaculite is a condensed sequence; conodonts in the Arkansas Novaculite indicate that it includes all the Devonian Period and the early Mississippian (Kinderhookian) as well. The flysch, by

contrast, is a very thick body of clastic turbidites, laid down in a rapidly subsiding trough. In the Ouachita Mountains the lower two formations, the Stanley Shale and Jackfork Sandstone, are as thick as 22,000 ft (6,700 m), thinning to the north. In the northern part of the mountains, the succeeding Johns Valley Shale and Atoka Formation are nearly as thick. Equivalent formations in the Marathon region are thinner, although still of impressive proportions.

The age of the lower part of the flysch sequence has long been disputed. At one time or another, the whole has been called Pennsylvanian by some, and all the sequence into the lower part of the Johns Valley Shale has been called Mississippian by others. Fossils are scarce and have been variously interpreted. Plant remains, broken and transported, have yielded ambiguous testimony (Miser and Hendricks, 1960, p. 1831). However, conodonts in the lower part of the Stanley are clearly Meramecian (Hass, 1950), and other fossils higher up are Chesterian; goniatites in the Jackfork are Morrowan (Gordon and Stone, 1969). The Mississippian fossils in the Johns Valley Shale are in transported blocks, derived from the Caney Shale in the foreland to the northwest.

On the Geologic Map, the Stanley Shale is labeled Mississippian (M) on the assumption that it is of Meramecian and Chesterian age, and the Jackfork Sandstone is labeled earliest Pennsylvanian (P_{1a}), or of Morrowan age. The Tesnus Formation of the Marathon region includes equivalents of both the Stanley and Jackfork; it contains Mississippian conodonts in the lower part and Pennsylvanian plants in the upper part. For convenience, all the Tesnus is labeled Mississippian (M) on the Geologic Map.

PENNSYLVANIAN

The Pennsylvanian System (P) is portrayed on the Geologic Map of the United States in the eastern two-thirds of the country; from the Rocky Mountains westward it is merged with the other upper Paleozoic systems into a single unit (uP , uPe). Within the region where it is mapped, the Pennsylvanian is classed as marine stratified rocks, even though it includes coal measures and other land-laid deposits, especially toward the east. No eugeosynclinal deposits are distinguished; they are known only in the extreme western part of the country, where those of Pennsylvanian age are merged with the rest of the upper Paleozoic (uPe).

The Pennsylvanian Period is essentially the same as the Upper Carboniferous of Europe; the Namurian Stage extends a little lower than the Pennsylvanian, into the American Chesterian Series. The Namurian, Westphalian, and Stephanian Stages, and others of European usage, are not widely referred to in North

America. Instead, classification is based on two sets of subdivisions—the coal measures sequence in the east consisting of the Pottsville, Allegheny, Conemaugh, and Monongahela Groups and the marine sequence in the west comprising the Morrowan, Atokan, Desmoinesian, Missourian, and Virgilian Series. Correlations between the two sets of units are known. The Morrowan and Atokan are approximately Pottsville; and the Desmoinesian, Missourian, and Virgilian are approximately Allegheny, Conemaugh, and Monongahela, respectively, except that the Conemaugh embraces somewhat more strata above and below than the Missourian. On the Geologic Map the two sets of names are used interchangeably; the Morrowan, Atokan, and Pottsville are indicated as P_1 , the succeeding units as P_2 , P_3 , and P_4 . The Pennsylvanian has also been subdivided into Lower, Middle, and Upper Pennsylvanian, the Lower Pennsylvanian being the Morrowan, the Middle Pennsylvanian the Atokan and Desmoinesian, and the Upper Pennsylvanian the Missourian and Virgilian; this is not useful for purposes of the Geologic Map.

Exposures of the Pennsylvanian sequence are mainly in the cratonic area, where it forms the centers of the basins and is the youngest Paleozoic rock preserved (fig. 9). Along the front of the Appalachian foldbelt, it forms the trough of the Allegheny synclinorium in Pennsylvania, West Virginia, Kentucky, and Alabama. A little of the Permian Dunkard Group overlies it in the north, and some outliers of Pennsylvanian rocks are preserved to the east in the folds of the Valley and Ridge province. Farther west, the Pennsylvanian forms a large area in the Illinois basin of Illinois, Indiana, and Kentucky, and a smaller area in the center of the Michigan basin. West of the Mississippi River it underlies an even larger area that extends from Iowa to Texas, with an extension eastward in the Arkoma basin of Oklahoma and Arkansas between the Ozark dome and the Ouachita Mountains foldbelt; the strata are mostly tilted westward beneath Permian rocks in the Prairie Plains homocline. All these areas were originally more nearly continuous; some of them are still almost connected by intervening outliers, and the sequences in the different areas can be closely matched with each other.

The Pennsylvanian System has been intensively studied, partly for its great deposits of coal toward the east and for its importance in petroleum exploration farther west. Its continental and marine deposits have an unprecedented multiplicity of lateral and vertical variations, accompanied by extreme persistence of many thin sedimentary units and a remarkable cyclic pattern of deposition in many regions, all suggestive of extreme tectonic stability. The record of land plants

and marine animals of the time is voluminous (Moore and others, 1944, p. 659).

The Pennsylvanian sequence is generally unconformable on the underlying Mississippian, especially in the northern Midwestern States, where it truncates the various subdivisions of the Mississippian at a low angle and extends downward across strata as old as Ordovician. Conformity with the Mississippian rocks occurs only along the edges of the Appalachian and Ouachita foldbelts. The Pennsylvanian is generally conformable with the Permian above in the Allegheny synclinorium and Prairie Plains homocline, and there have been considerable differences through the years in the placement of the boundary between the two systems.

The Pennsylvanian sequence is about 3,000 ft (900 m) thick in the Allegheny synclinorium, thinnest in the north and thicker southwestward mainly because of increase in the Pottsville Group at the base. In Alabama, Pennsylvanian rocks are 10,000 ft (3,000 m) thick, with the Pottsville alone represented. In most of the Illinois basin to the west the sequence is less than 2,000 ft (600 m) thick, but it thickens to the south to about 3,000 ft (900 m). West of the Mississippi River, the Pennsylvanian rocks are less than 2,000 ft (600 m) thick in the northern part of the Prairie Plains homocline, but they thicken southward in Oklahoma and Arkansas, mainly by wedging in of the Morrowan and Atokan Series at the base. Along the front of the Ouachita Mountains in Arkansas, the Atoka Formation alone is 18,000 ft (5,500 m) thick, but it thins rapidly northward across the Arkoma basin to a featheredge along the front of the Ozark dome 80 mi (130 km) to the north.

The Pennsylvanian rocks are dominantly nonmarine and coal bearing to the east and dominantly marine to the west, but the two types of deposits are complexly interfingered in very thin units. Through much of the Interior Region, the sequence consists of cyclical units, or cyclothems. In the Illinois basin, a typical cyclothem begins with sandstone, resting on a channeled surface, followed by sandy shale, freshwater limestone, underclay, and coal, which is overlain by gray and black shale and marine limestone (Wanless, 1962, p. 49–50). In the Allegheny synclinorium, nonmarine elements dominate and the coals are thicker, but fossiliferous marine limestones persist into Ohio and western Pennsylvania (Branson, 1962, p. 199). In Kansas, each cyclothem is dominantly marine shale and various kinds of limestone, but a coal bed sometimes occurs in the lower part (Merriam, 1963, p. 103–108). Each cyclothem and its subdivisions are traceable for scores or hundreds of miles. The ultimate cause of the cyclical sedimentation is uncertain, but the rock record indi-

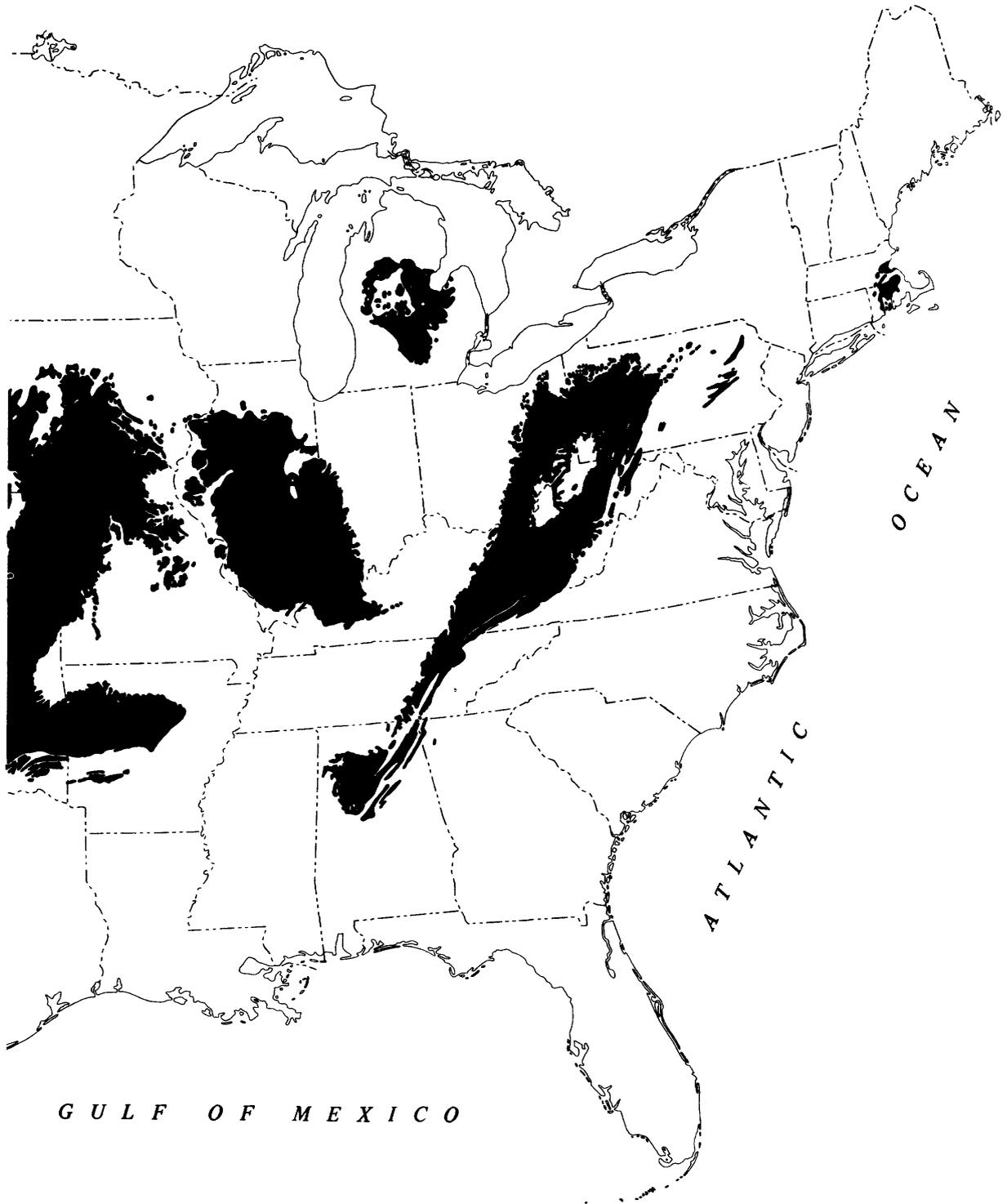


FIGURE 9.—Eastern United States, showing areas mapped as Pennsylvanian on Geologic Map of United States. Includes units of marine and nonmarine stratified rocks (P) and their subdivisions (P₁, P_{1a}, P₂, P₃, P₄).

cates fluctuating deposition of level surfaces near sea level under conditions of great stability.

In the northern Midwestern States, sedimentological studies indicate that the sandstone beds were derived from the north, from crystalline areas in the Canadian Shield, and some of the channels in which they were transported have been traced. Farther south and southeast, a greater proportion of the clastics was derived from the Appalachian and Ouachita foldbelts.

In Alabama, the thick Pottsville sequence is all shallow-water, with coal beds at intervals throughout. It joins in the subsurface beneath the Mississippi Embayment with the equally thick or thicker Atoka Formation of the Arkoma basin, which is a deep-water flysch or turbidite that filled a rapidly subsiding trough along the northern edge of the Ouachita foldbelt. A depth change between the two is indicated and is duplicated in the Atoka itself, which changes northward toward the Ozark uplift into a shallow-water deposit more like the Pottsville.

The underlying Jackfork Sandstone (P_{1a}) and Johns Valley Shale, of Morrowan age, are also flysch facies. A remarkable feature of the Johns Valley in the frontal belts of the Ouachita Mountains is the occurrence of wildflysch, or beds containing blocks and slabs a hundred feet or more (30–60 m) across of older formations of the cratonic sequence to the north and northwest. Similar block beds occur in the Marathon region of western Texas, but at a somewhat higher level, in the Haymond Formation of Atokan age.

In the Arkoma and Ardmore basins north and west of the Ouachita Mountains, an important discontinuity is indicated at the top of the Atokan Series by a moderate unconformity at the base of the Desmoinesian and by the occurrence in the Desmoinesian of conglomerates derived from the Ouachita Mountains. These suggest that much of the deformation in the Ouachita foldbelt had been completed by the end of Atokan time. This is confirmed by drilling in the Coastal Plain south of the Ouachita Mountains, where fossiliferous Desmoinesian carbonates lie undeformed on steeply folded Ouachita rocks.

The Pennsylvanian sequence in north-central Texas is separated from that in the remainder in the Prairie Plains homocline to the north by overlapping Cretaceous deposits but is broadly similar. It has long been divided into the Bend, Strawn, Canyon, and Cisco Groups. The Bend Group (including the prominent Marble Falls Limestone) is of Morrowan and Atokan age and is unconformable beneath the Strawn Group which overlaps it from the east. The Strawn and Canyon Groups are broadly equivalent to the Desmoinesian and Missourian Series, but the original Cisco

Group has now been partitioned between the Virgilian Series and the basal Permian Wolfcampian Series.

Most of the outcrops of Pennsylvanian age have been divided on the Geologic Map into the four divisions (P₁, P₂, P₃, and P₄), but for various reasons the Pennsylvanian is not divided in the smaller outlying areas. In the Marathon region of western Texas, the undivided Pennsylvanian (P) includes the Dimple Limestone and Haymond Formation, which are flysch deposits of Morrowan and Atokan age, and the thinner shallow-water Gaptank Formation that embraces the rest of the Pennsylvanian System into the Virgilian Series. In Pennsylvania and Maryland the Pennsylvanian is undivided in the outlying downfolds in the Valley and Ridge province—the Anthracite basins, the Broadtop basin, and the Georges Creek basin. The subdivisions of the main Pennsylvanian area are recognizable in these outliers, but their outcrops are too narrow for representation on the scale of the Geologic Map.

Also shown as undivided Pennsylvanian (P) are the rocks of the Narragansett and Boston basins in southeastern New England, whose precise correlation with the standard sequences is less certain. They lie unconformably on earlier Paleozoic and Precambrian metamorphic and plutonic rocks and are postorogenic to their deformation (Quinn and Oliver, 1962). However, they themselves are steeply folded and along the south coast are intruded by the late Paleozoic Narragansett Pier Granite (P_{g3}). The rocks of the Narragansett basin are at least 10,000 ft (3,000 m) thick and consist largely of sandstone and shale of gray to black color, with some redbeds in the lower part in the north. Conglomerates composed of pebbles and boulders of the surrounding rocks occur at the base and at intervals higher up in the sequence, and there are a few beds of coal, largely altered to graphite. Fossil plants are fairly abundant and indicate a middle Pennsylvanian age. The rocks of the Boston basin to the northeast are 5,000 ft (1,500 m) or more thick and differ somewhat from those of the Narragansett basin. A few late Paleozoic plants have been collected but do not furnish data for firm correlation. The rocks of the Boston basin may be older than those of the Narragansett basin. A younger, or Permian, age has been claimed for them on the basis of an alleged tillite (Squantum Tillite Member of Roxbury Conglomerate), but this deposit is probably neither Permian nor a tillite.

PERMIAN

The Permian System (P) is shown on the Geologic Map of the United States in a small area in the Ap-

palachian Region, in extensive areas in the Midcontinent Region, and in parts of the Cordilleran Region. Elsewhere in the Cordilleran Region, from the Rocky Mountains westward, it is merged with the remainder of the upper Paleozoic (uP, uPe). Most of it is classed as marine stratified rocks, although some of it is actually of continental origin. In a few areas in California, Permian eugeosynclinal deposits (Pe) are separated from the remainder of the upper Paleozoic. In the Midcontinent Region and Colorado Plateau, the Permian is divided into its four series (P₁, P₂, P₃, P₄), and some of these are divided into smaller subdivisions (P_{2a}, P_{2b}, P_{3a}, P_{3b}), the meaning of which is explained below.

The Permian is the youngest system of the Paleozoic Era. Its type area is in European Russia, where it was proposed by Murchison in 1841 to supplant older terms such as Dyas that had been in use in western Europe for Paleozoic strata above the Carboniferous (Dunbar and others, 1960, p. 1764-1767). In the United States, the type area is in the richly fossiliferous marine strata of western Texas, where exposures in various mountain ranges (especially the Glass and Guadalupe Mountains) are divided into the Wolfcampian, Leonardian, Guadalupian, and Ochoan Series (P₁, P₂, P₃, P₄) (Adams and others, 1939). The Permian has also been divided into Lower and Upper Permian (with a somewhat uncertain boundary between them in the United States), but these are not useful for the Geologic Map.

The position of the base of the Permian has fluctuated through the years, the common tendency being to move it downward. As originally defined by Murchison, the lower division was the Kungurian Series, and the underlying Artinskian Series was included in the Carboniferous System. Later it was realized that the Artinskian was, in fact, younger than any Carboniferous rocks in western Europe, and so it was accordingly added to the Permian System. At present, the base of the Permian is placed below the Sakmarian Series (originally a lower division of the Artinskian), which is equivalent to the Wolfcampian in the United States. This basal unit is especially characterized by the zone of the fusulinid *Pseudoschwagerina*.

At most places the Permian sequence is conformable on the underlying Pennsylvanian. The contact is unconformable in parts of west Texas, as a result of orogenies in the adjacent Ouachita foldbelt. Throughout the United States the Permian is everywhere unconformable with the overlying Mesozoic rocks and especially with the Triassic System where it is present. In the west Texas standard area, the overlying strata are Upper Triassic. In the Cordilleran Region farther west, Lower Triassic rocks are common, but the highest Permian stage is Leonardian or Guadalupian; so, a considerable gap exists, representing latest Permian

time. Commonly, the unconformity at the top is not structural, and in parts of the Cordilleran Region the Permian and Triassic Systems are rigidly parallel for long distances, even though a hiatus exists between them.

APPALACHIAN REGION

The Dunkard Group (P₁) occupies the deeper part of the Allegheny synclinorium in Pennsylvania, Ohio, and West Virginia as erosional remnants on top of the Monongahela Group (P₄) (fig. 10). Its preserved thickness is about 1,200 ft (400 m), but it was probably originally much thicker. The Dunkard is dominantly nonmarine. A few limestone beds in the northwestern exposures suggest vague marine connections, but the remainder is nonmarine shale, partly red, and sandstone. A few coal beds occur but not as abundantly as in the Pennsylvanian System, prompting the early term "Upper Barren Measures" for the group. As in the Pennsylvanian strata beneath, the different rock types are arranged in cyclical order.

Fossils in the Dunkard Group are sparse (Berryhill, 1967; Barlow, 1972). They include vertebrates, insects, freshwater invertebrates, and plants. Only the plants offer much indication of precise age; most of them are characteristic Pennsylvanian types, but they also include *Callipteris conferta*, which is commonly considered to be a Permian index fossil and is the chief basis for the traditional classification of the group as early Permian. Nevertheless, this assignment has been questioned by some who would prefer to place the group in the late Pennsylvanian. On the Geologic Map, the Dunkard Group is classed as early Permian (P₁), or approximately equivalent to the Wolfcampian Series farther west.

SOUTHWESTERN UNITED STATES

Permian rocks extend continuously in a wide band in the Midcontinent Region from Nebraska to central Texas, where they are part of the west-tilted Prairie Plains homocline (fig. 10). They are also exposed in west Texas and eastern New Mexico on the opposite flank of the intervening West Texas Permian basin. The central part of the basin is covered by Mesozoic and Cenozoic rocks, but the connection between the Permian rocks on the two sides has been traced in detail by closely spaced drilling. An outlying area to the south, in the Glass Mountains, duplicates the formations of northern west Texas. Farther west in New Mexico, Permian rocks are exposed on the flanks of many of the block mountains, and still farther west in northern Arizona they spread across the southern part of the Colorado Plateau to the western end of the Grand Canyon. In all these areas, dips are sufficiently

low and outcrops correspondingly so broad that the Permian rocks are subdivided in detail on the Geologic Map.

The thickness of the Permian sequence is about 1,000 to 3,000 ft (300–900 m) in Kansas, thinning northward to disappearance in Nebraska and thickening southward to 10,000 ft (3,000 m) in surface sections in west Texas and to as much as 18,000 ft (5,500 m) in the subsurface. In the Grand Canyon area to the west, it is about 2,000 ft (600 m) thick.

Classification of the Permian sequence in the region is based on standard sections in west Texas, where the Wolfcampian, Leonardian, Guadalupian, and Ochoan Series (P₁, P₂, P₃, P₄) are named and defined. All the series except the Ochoan at the top are open-sea marine deposits and are richly fossiliferous. The Ochoan is an evaporite deposit, the thick Castile Anhydrite and Salado Halite, with the thin Rustler Dolomite at the top. The Rustler contains the only fossils, a scanty fauna of brachiopods and mollusks that are unmistakably Paleozoic.

Difficulties are encountered in extending the west Texas subdivisions outside the type area; assignment of beds near the middle to either the Leonardian or the Guadalupian Series is especially controversial, as explained below. The west Texas strata formed in a circumscribed area, the Delaware basin, that was nearly surrounded by carbonate barriers, culminating in the great Capitan Limestone reef in the upper part of the Guadalupian. Outside the basin, deposits were laid down in shallower water, in evaporite pans, or on low surfaces that received redbed deposits. Large numbers of the fossils characteristic of the basin fail to extend into these outside areas. Many problems thus exist regarding the proper classification of the much larger area of Permian rocks to the north, resulting in some uneasy compromises on the Geologic Map. These will probably satisfy no dedicated stratigrapher but are explained in the correlation diagram included at the bottom of the legend. In each general area, a feasible subdivision is possible, but correlations between the areas that are implied on the map are not necessarily realistic.

MIDCONTINENT REGION

In the Midcontinent Region, from central Texas to Nebraska, Permian outcrops are continuous, and equivalent units are traceable from one end to the other. The only complication is near the Arbuckle and Wichita Mountains in southern Oklahoma and northern Texas, where the Wolfcampian and lower part of the Leonardian Series (upper Cisco Group and Wichita Group) pass into a red arkosic continental facies (P_{1c}, P_{2ac}). On the map, the southern edge of these deposits in Texas is drawn to include localities where verte-

brate fossils are abundant. Subdivisions are difficult to trace through the red continental deposits. The Coleman Junction Limestone, which is the dividing marker between the Wolfcampian and Leonardian Series farther south, disappears, but a uraniferous sandstone near its level persists and is identifiable by radiometry (Chase, 1954). South of the continental deposits the upper part of the Cisco Group and the Wichita Group (here originally called the "Albany Formation") are marine fossiliferous shales and limestones. North of the continental deposits, the Wolfcampian Series (Admire, Council Grove, and Chase Groups of Kansas) is likewise marine shales and limestones, but the lower Leonardian (Sumner Group) consists of red deposits and includes in subsurface the thick salt beds of the Wellington Formation. The higher Leonardian (P_{2b}) is red throughout and includes the Clear Fork Group in Texas and the Nippewalla Group in Kansas. These red deposits, and those higher up in the Permian, are classed with the marine deposits on the map. They consist of persistent layers of red shale, gypsum, and thin carbonates that are widely traceable; probably they were laid down on broad level surfaces which maintained at least tenuous connections with the sea.

Above these strata in the Midcontinent Region are two well-defined bodies of rocks, the El Reno (= Pease River) Group and the Whitehorse Group (P_{3a}, P_{3b}), each marking a distinct cycle of sedimentation and each at least locally having a disconformity at the base. At the base of the El Reno is sandstone (San Angelo or Duncan), followed by red shales (Flowerpot and Dog Creek) which contain variable thicknesses of gypsum and dolomite (Blaine). In Texas, the Blaine contains a sparse invertebrate fauna including the ammonoid *Perrinites hilli*. Correlation with the west Texas standard section is controversial. The *Perrinites* occurs no higher than the Leonardian Series, but down to the west, in the subsurface, beds equivalent to the Blaine contain lower Guadalupian parafusulinids (*Parafusulina rothi*). On the Geologic Map, the group is classed as lower Guadalupian (P_{3a}), but with misgivings. The succeeding Whitehorse Group (P_{3b}) is a more uniform deposit than the beds below, with a lighter red color, and is divided into the Marlow Formation (shaly) and the Rush Springs Sandstone. Above the Rush Springs is the Cloud Chief Gypsum, generally excluded from the group but part of the same depositional cycle. Channel sandstones in the Marlow Formation contain a small fauna of marine invertebrates (Newell, 1940) identical with those in the backreef upper Guadalupian rocks (Artesia Group) in southeastern New Mexico, and correlation with these beds is further assured by subsurface tracing across the West Texas basin.

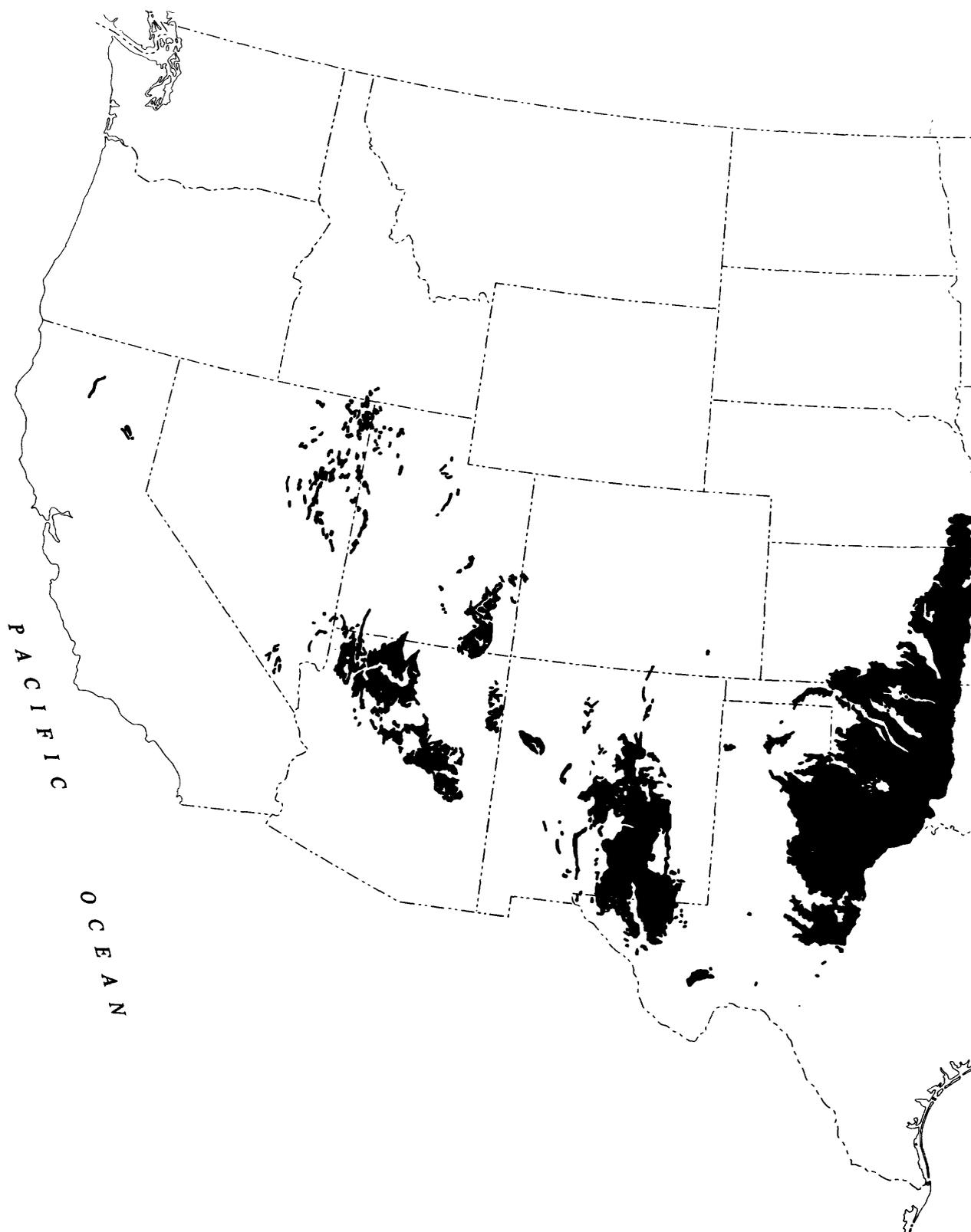


FIGURE 10.—United States, showing areas mapped as Permian on Geologic Map of United States. Includes units of marine and nonmarine stratified rocks (P) and their subdivisions (P1, P2, P2a, P2b, P3, P3a, P3b, P4), continental deposits (P1c, P2ac), and eugeosynclinal deposits (Pe). Does not include many small outcrops in Cordilleran Region which are merged with the remainder of the upper Paleozoic (uP, uPe).

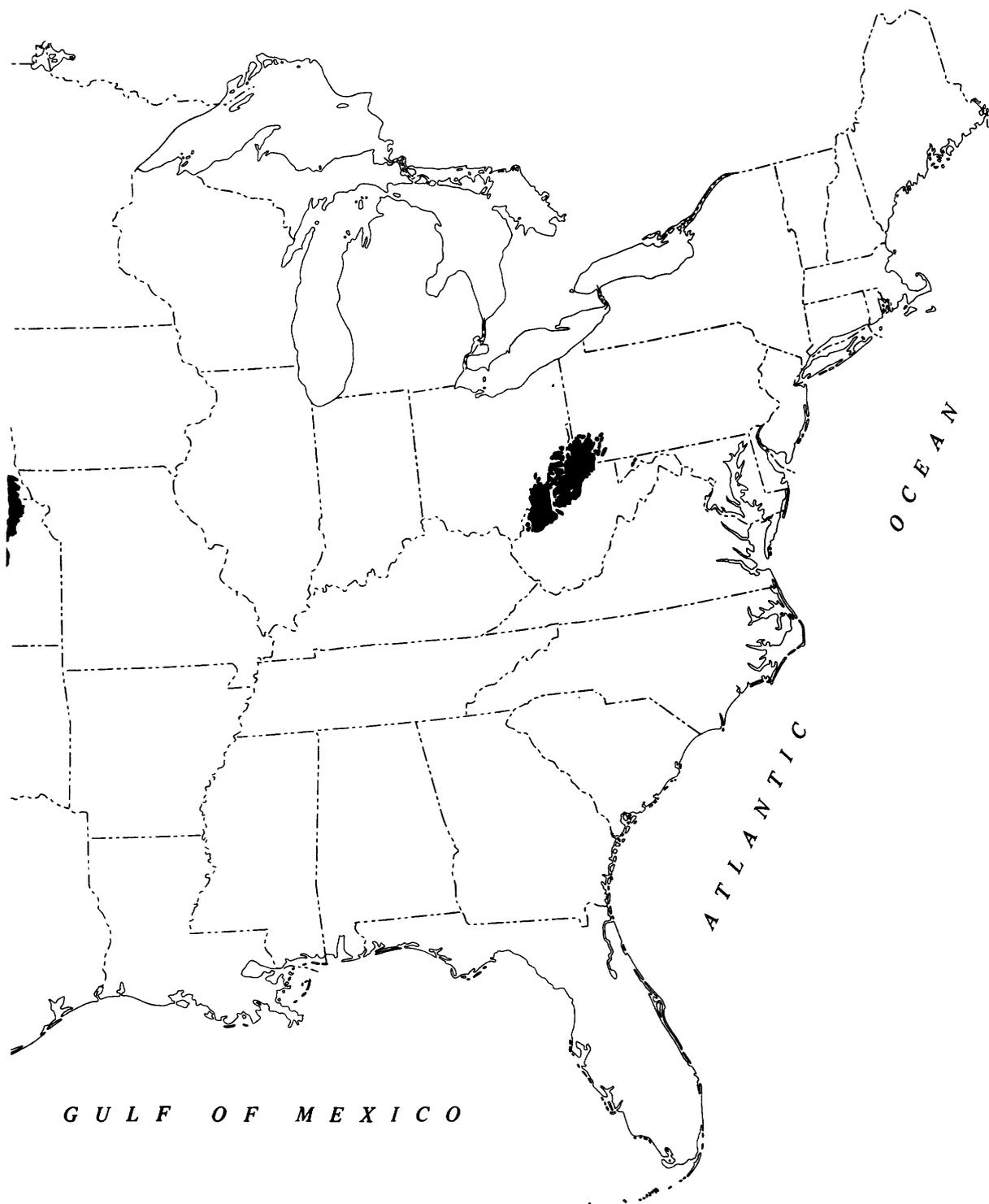


FIGURE 10.—Continued.

The uppermost Permian deposits of the Midcontinent Region are the redbeds of the Quartermaster Formation, which are discontinuously exposed in Texas and Oklahoma beneath Mesozoic and Cenozoic deposits. The basal layer in Texas, the Claytonville Dolomite, is traceable westward in the subsurface into the Salado Halite and Rustler Dolomite of the Ochoan Series, and the Quartermaster must be the shoreward edge of the great evaporite sequence of the West Texas Permian basin; it is shown as P₄ on the Geologic Map.

NEW MEXICO

In eastern New Mexico, rocks equivalent to those in the Midcontinent Region reappear on the western margin of the West Texas basin, where they are represented by the Abo Sandstone, Yeso Formation, Glorieta Sandstone, San Andres Limestone, and Artesia Group.

The Abo Sandstone is a red continental deposit containing plant and vertebrate fossils that interfingers southward near the Texas border with the marine Wolfcampian Hueco Limestone and hence is classed as P_{1c}. Some marine Wolfcampian rocks persist locally at the base (Bursum Formation) but are not separated on the Geologic Map from the Pennsylvanian (uP).

The Yeso Formation is a redbed sequence, with beds of carbonate and evaporite, of lower Leonardian age (P_{2a}). The Glorieta Sandstone is a thin deposit that interfingers laterally with both the Yeso and San Andres units. The San Andres Limestone has by far the largest surface area of the Permian rocks of eastern New Mexico and is the caprock of many mountain ranges and plateaus. Like the El Reno Group of the Midcontinent Region, to which it appears to be broadly equivalent, its age with respect to the west Texas standard sequence is controversial. Its brachiopods and other invertebrate fossils, including *Perrinites hilli*, are Leonardian forms, but Guadalupian parafusulinids occur, especially in the eastern exposures. The limestone is not divided on the source map (Geologic Map of New Mexico of 1965), and it is all indicated on the Geologic Map as Leonardian (P_{2b}). Very likely, however, it is a composite unit. During recent mapping in the southeastern part of the State, Kelley (1971, p. 7-14) divided it into the Rio Bonito, Bonney Canyon, and Fourmile Draw Members. The Rio Bonito, or thick-bedded lower part, is the only member represented in the type San Andres Mountains to the west and is the most likely candidate for a Leonardian age. The two higher members, and especially the evaporitic Fourmile Draw Member at the top, are more likely Guadalupian, and the Fourmile Draw seems to be traceable into the middle Guadalupian beds in the Guadalupe Mountains.

The succeeding Artesia Group (P_{3b}) is clearly equivalent to the upper Guadalupian of the Guadalupe Mountains and has been traced in the subsurface into the Whitehorse Group of the Midcontinent Region. It is partitioned horizontally into five formations (Grayburg, Queen, Seven Rivers, Yates, and Tansill), but each of these changes facies northward from backreef carbonates in the Guadalupe Mountains into evaporites and redbeds in the Pecos Valley.

The overlying Ochoan evaporitic formations (P₄) in the southeastern corner of the State are part of the type Ochoan Series.

NORTHERN ARIZONA

The Permian of northern Arizona is divided into the Supai Formation, Hermit Shale, Coconino Sandstone, and the Toroweap and Kaibab Limestones.

The Kaibab and Toroweap form by far the greatest area of exposure, as they are the limestone caprock of this part of the Colorado Plateau. The Toroweap is a minor local unit, formed in a separate sedimentary cycle, but it is not greatly different in age from the Kaibab. Rather abundant brachiopods and other invertebrate fossils indicate that both are Leonardian (P_{2b}); they are seemingly equivalent to the San Andres Limestone in New Mexico to the east, although the surface continuity is broken by cover of Mesozoic deposits.

The three Permian formations beneath are more heterogeneous and have a wider range in age, but they occupy much smaller outcrop areas. The white Coconino Sandstone is a continental dune deposit without fossils except for vertebrate tracks. The red Hermit Shale below contains an abundant flora, probably of early Leonardian age. The thicker red Supai Formation is largely Wolfcampian. It interfingers with marine Wolfcampian rocks (Pakoon Formation) at the western edge of the plateau, but at a few places elsewhere the Supai includes some strata of Pennsylvanian age in the lower part. Because of the small outcrop area of these formations, they are all marked on the Geologic Map as lower Leonardian (P_{2a}).

Northward in the Colorado Plateau in Utah, the Permian System emerges in small to large areas in the higher uplifts but is not subdivided (P). The largest area is in the Monument unwarped in the south part of Utah, where the rocks consist of units of sandstone like the Coconino and units of redbeds; these units are classed as members of the Cutler Formation, which has an age range nearly equal to the whole Grand Canyon sequence. A little limestone, classed as Kaibab but probably younger, appears at the top of the Permian in the San Rafael Swell but in areas too small to be differentiated.

CORDILLERAN REGION

Marine Permian rocks, with age ranges from Wolfcampian to Guadalupian (= Phosphoria), are about 5,000 ft (1,500 m) thick in the eastern Great Basin of Nevada and Utah and in many places form sufficiently large areas to be differentiated on the Geologic Map (P); elsewhere, the Permian is merged with the remainder of the upper Paleozoic (uP).

EUGEOSYNCLINAL DEPOSITS

Permian eugeosynclinal deposits in the western part of the Cordilleran Region are mostly merged with the other upper Paleozoic deposits (uPe) or are included in the Triassic and Permian eugeosynclinal deposits (TPe), but they are separately shown in a few areas in northern California.

In the Taylorsville area of the northern Sierra Nevada are the volcanic and volcanoclastic Arlington, Reeve, and Robinson Formations, which in a few places contain large parafusulinids of Permian age and in others the Permian fish *Helicoprion* (McMath, 1966, p. 179-180).

In the eastern part of the Klamath Mountains farther north are the McCloud Limestone, Nosoni Formation (mudstone and tuff), and the Dekkas andesite, about 6,000 ft (1,800 m) thick. All are fossiliferous; fusulinids and corals of Wolfcampian and Leonardian age occur in the McCloud, and fossils in the Dekkas are of Guadalupian (Capitan) age (Albers and Robertson, 1961, p. 21-30).

UPPER PALEOZOIC

From the Rocky Mountains westward, the Mississippian, Pennsylvanian, and Permian Systems form such small outcrops, either singly or together, that they are combined on the Geologic Map of the United States into a unit of upper Paleozoic, with a distinction between marine stratified rocks (uP) and eugeosynclinal deposits (uPe). In some areas, as explained above, the Permian (P) forms outcrops sufficiently extensive for representation and partial subdivision; elsewhere, it is merged with the other systems.

MARINE STRATIFIED ROCKS (uP)

As in the lower Paleozoic systems, the marine stratified rocks of the upper Paleozoic systems of the Cordilleran Region formed partly in a cratonic area and partly in a miogeosynclinal area, the geographic positions in each being essentially the same (fig. 11). However, the deposits in the two areas are much more varied than before, reflecting, in large part, the greater crustal unrest of later Paleozoic time.

The shifting patterns of distribution of the different systems in the cratonic area are illustrated in the "Geologic Atlas of the Rocky Mountain Region" (Malory, 1972; see also fig. 12). The three systems were originally nearly continuous in the miogeosynclinal area to the west, although their continuity is now broken by subsequent erosion or by burial beneath younger deposits.

MISSISSIPPIAN

Mississippian rocks are widely distributed in the cratonic area, the only exception being in parts of Colorado and northern New Mexico. In Colorado, they may originally have been more extensive but were removed by erosion during the disturbances of Pennsylvanian and later times; however, in much of northern New Mexico they were probably never deposited.

In the exposures in the mountain ranges of the cratonic area, the Mississippian sequence is from 500 to 2,000 ft (150-600 m) thick. A striking feature is the great sheet of carbonate rocks of middle Mississippian age (mainly Osagean, partly Meramecian, but with variable upper and lower limits from place to place), typified by the Madison Limestone of the Northern Rocky Mountains but including the Rundle of the Canadian Rocky Mountains, the Pahasapa of the Black Hills, the Redwall of the Grand Canyon, the Escabrosa of southern Arizona, and other named units in local areas. Higher Mississippian rocks, including Chesterian, are of more local extent, and lowest Mississippian rocks, or Kinderhookian, are scantily developed.

In the miogeosynclinal area to the west, the Mississippian sequence is generally thicker, but in variable amounts, indicating mild tectonic activity. It is 7,000 ft (2,100 m) thick in an irregular area in northwestern Utah, where it represents the initial deposits of the Oquirrh basin, a paleotectonic feature characterized by thick shallow-water deposits laid down in an area of unusual subsidence that culminated during Pennsylvanian time. The Mississippian deposits are mainly limestone but include some shale units; they are notable for including an unusually complete sequence from Devonian to Pennsylvanian, or from Kinderhookian through Chesterian time. Another maximum of 7,000 ft (2,100 m) of Mississippian strata occupies a linear trough farther west in central Nevada, along the edge of the Antler orogenic belt, whose deposits are of quite different character. The lower Mississippian unit (Joana Limestone) is inconsequential, and most of the sequence is middle or upper Mississippian clastic deposits—the Chainman Shale and the overlying or interfingering quartzites and conglomerates of the Diamond Peak Formation. They are part of a clastic wedge derived from the orogenic belt to the west and

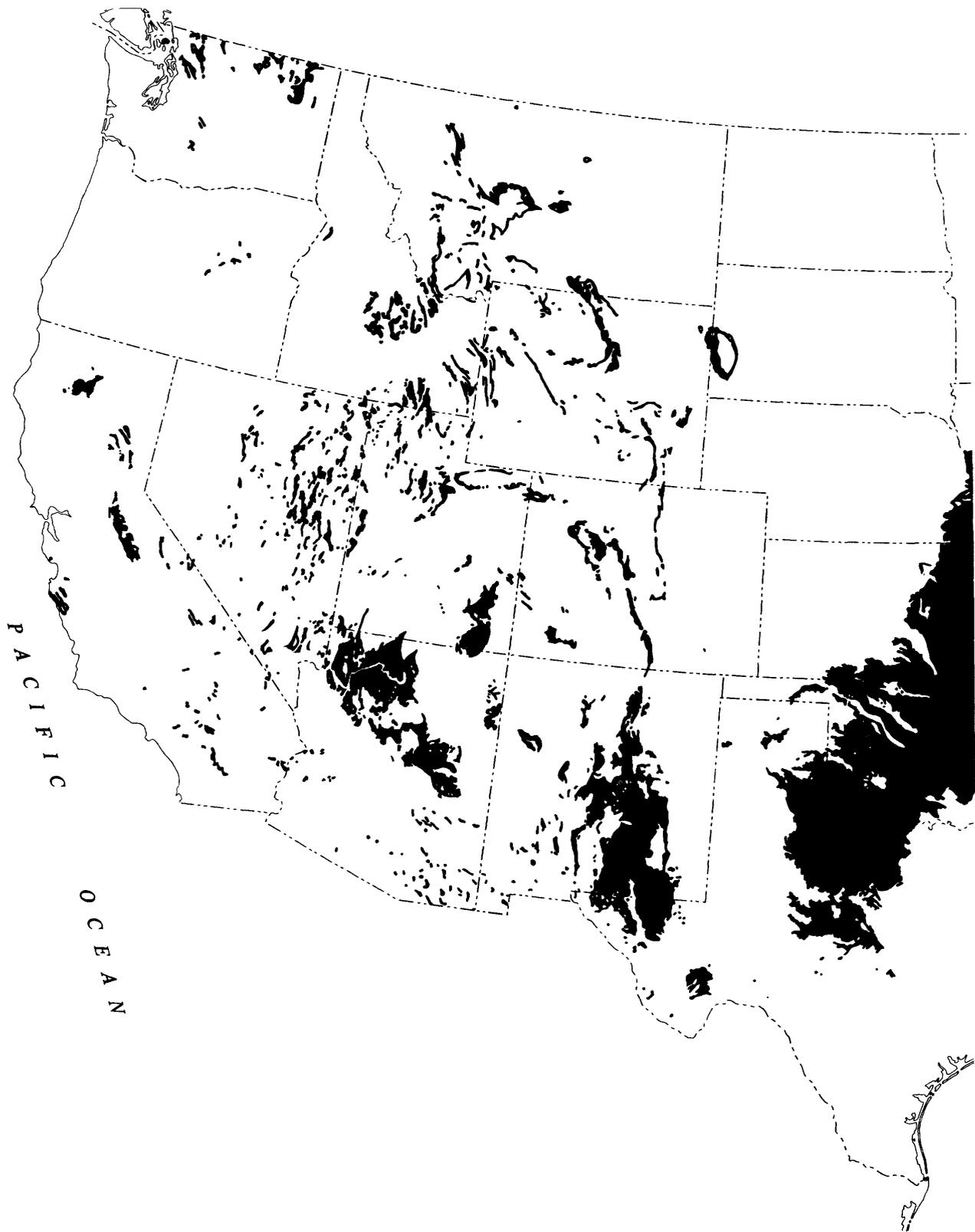


FIGURE 11.—Western United States, showing areas mapped as upper Paleozoic on Geologic Map of United States. Includes units of marine stratified rocks (uP), Mississippian rocks (M), Pennsylvanian rocks (P, P₁, P₂, P₃, P₄), Permian rocks (P, P₁, P_{1c}, P₂, P_{2a}, P_{2ac}, P_{2b}, P₃, P_{3a}, P_{3b}, P₄), clastic wedge, ge deposits (uPc), and eugeosynclinal deposits (uPe, Pe).

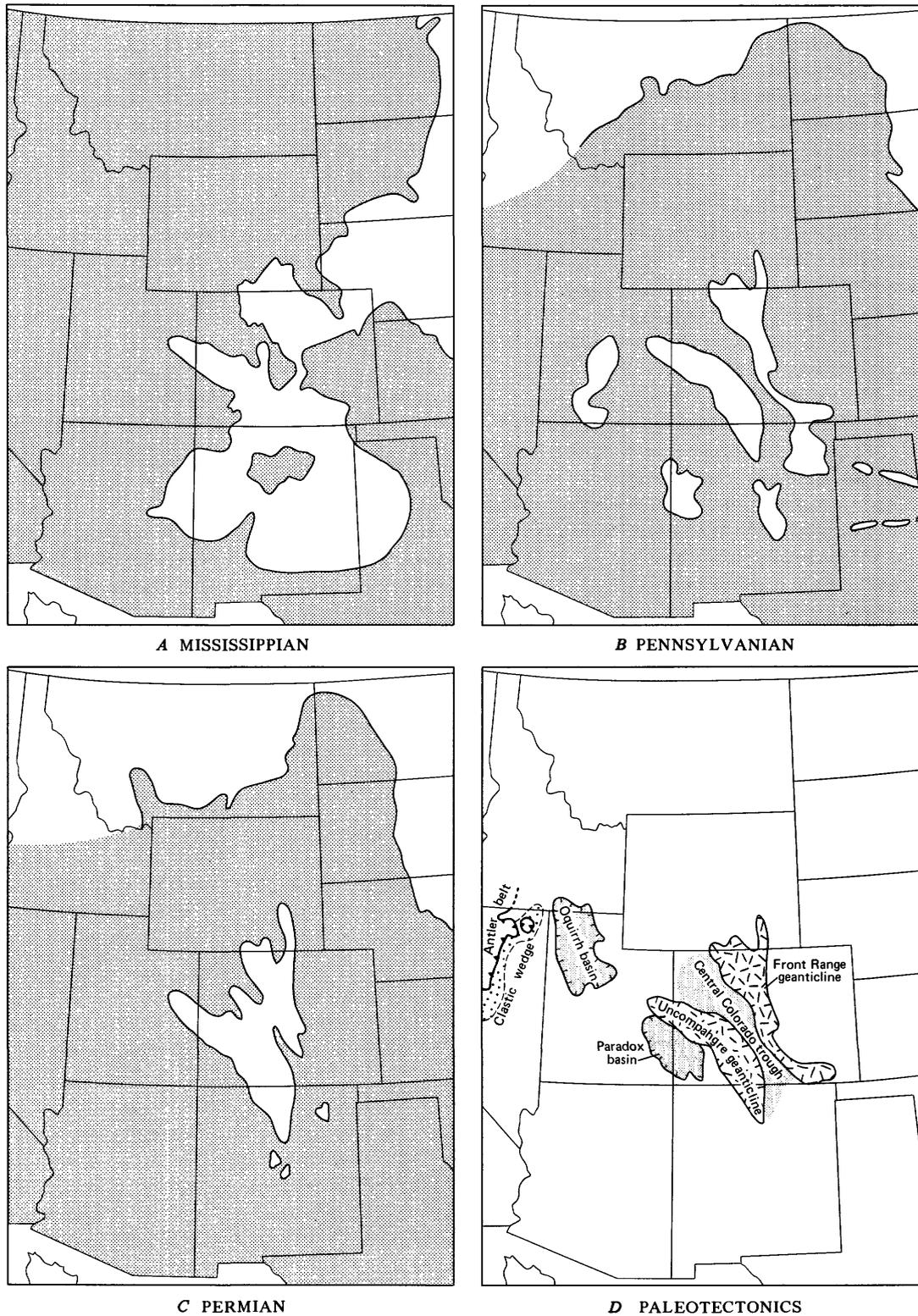


FIGURE 12.—Eastern part of Cordilleran Region, showing surface and subsurface extent of the systems grouped as upper Paleozoic on Geologic Map and some of the paleotectonic features of the time: *A*, Mississippian. *B*, Pennsylvanian. *C*, Permian. *D*, Paleozoic tectonic features. Compiled from Geologic Atlas of Rocky Mountain Region (Mallory, 1972) and other sources.

are separately shown on the Geologic Map as a clastic wedge facies (uE_c). Also so mapped are the Mississippian Milligen Formation and the Pennsylvanian Wood River Formation of south-central Idaho, which are clastic wedge deposits derived from orogenic belts farther west.

PENNSYLVANIAN

Pennsylvanian deposits in the cratonic area are much more varied than in any of the preceding Paleozoic systems, owing mainly to intracratonic orogenic activity on the site of the Southern Rocky Mountains, which produced the Colorado system of structures, or "Ancestral Rocky Mountains" (Mallory, 1972). Two geanticlines were raised: the Front Range geanticline on the site of the present Front Range and some ranges to the west, and the Uncompahgre geanticline that extended southeastward from the Uncompahgre Plateau of western Colorado across the site of the San Juan Mountains into northern New Mexico. The northeastern geanticline was raised somewhat earlier than the southwestern, although clastic deposits were shed off both of them through Pennsylvanian into Permian time. Between the two geanticlines was a deeply subsiding linear basin, the Central Colorado trough, which received as much as 12,000 ft (3,700 m) of clastic sediments during Pennsylvanian time.

Few structures attributable to the Pennsylvanian orogeny can be identified, and their record is mainly derived from the red clastic deposits along the flanks, including such units as the Fountain Formation on the eastern edge of the Front Range and the Sangre de Cristo Formation of the Sangre de Cristo Mountains (derived from the southeastern end of the Uncompahgre geanticline). Southwest of the Uncompahgre geanticline in southwestern Colorado and eastern Utah is the Paradox basin, another area where Pennsylvanian deposits are over 7,000 ft (2,100 m) thick; here, however, the greater part of the sequence is evaporite, mainly halite, but includes layers of potash salt.

North and south of the Colorado system in the cratonic area, the Pennsylvanian is no more than 1,000 ft (300 m) or so thick and largely carbonate; it includes the Amsden and Tensleep Formations of Wyoming, the main part of the Naco Group in southern Arizona, and the Magdalena Group in New Mexico. In central New Mexico, the Magdalena rests directly on Precambrian rocks in most places; Mississippian rocks are sporadic and the lower Paleozoic sequence wedges out northward in the southern part of the State.

The Pennsylvanian sequence is not more than 2,000 or 3,000 ft (600–900 m) thick in most of the

miogeosynclinal area, but it thickens to as much as 13,000 ft (4,000 m) in the Oquirrh basin of northwestern Utah. Most of this sequence is the Oquirrh Formation, whose base is of Morrowan age and whose upper part extends into Wolfcampian time (not divided on the Geologic Map). The formation consists of interbedded limestones and sandstones, the latter made up of fine-grained clean quartz sands. The sands could not have been derived from any orogenic area; apparently they came from the craton (where similar sandstones of lesser thickness occur) and were trapped in a unique restricted area of exceptional subsidence in the miogeosyncline.

Farther west in the miogeosyncline, in the Ely and Eureka areas, Nevada, the Pennsylvanian is represented by the Ely Limestone, which succeeds the clastic wedge deposit of the Diamond Peak Formation. Pennsylvanian rocks also occur in the Winnemucca area still farther west, where they are unconformable on "transitional" and eugeosynclinal lower Paleozoic rocks of the Antler orogenic belt. Some is limestone, but the conglomeratic middle Pennsylvanian Battle Formation is included. Also included in the upper Paleozoic in this area on the Geologic Map are Permian units, the upper part of the Antler Peak Limestone and the Edna Mountain Formation, the latter with high Permian (Phosphoria) fossils (Roberts and others, 1958, p. 2841–2844).

PERMIAN

As indicated above, the more extensive areas of Permian rocks in the Cordilleran Region are separately mapped and in part subdivided; however, narrower belts of outcrop elsewhere are merged with the remainder of the upper Paleozoic.

Through most of the cratonic area the Permian sequence is no more than 1,000 or 2,000 ft (300–600 m) thick. Near the previously formed uplifts in Colorado, it is mostly red clastic deposits, an upward continuation of those of the Pennsylvanian, but finer grained. Southwestward and southward, carbonate rocks appear in the Leonardian Series (separately mapped as the Kaibab, Toroweap, and San Andres Limestones, P₂b). Northward, an important component is the complex of marine deposits that includes the Park City and Phosphoria Formations, the first shallow-water limestone, the second deep-water phosphatic shale and chert. Although the older part of the complex is Leonardian, the main body is Guadalupian and contains many of the same marine fossils as are found in the standard Guadalupian section in west Texas. Eastward across Wyoming, the complex of marine deposits intertongues with redbeds of the Chugwater and Goose Egg Formations.

In the miogeosynclinal belt to the west, thicknesses of Permian rocks as great as 10,000 ft (3,000 m) are recorded in parts of northwestern Utah, mostly an upward continuation of the Oquirrh Formation, and are included in the upper Paleozoic (uP) on the Geologic Map. Somewhat thinner sequences elsewhere in western Utah and in eastern Nevada form prominent areas of outcrop and are shown as undivided Permian (P). The westernmost of these, the Carbon Ridge and Garden Valley Formations of the Eureka district, are dominantly clastic deposits that lie unconformably on the rocks beneath—the Carbon Ridge on miogeosynclinal rocks, the Garden Valley on lower Paleozoic eugeosynclinal rocks (Vinini Formation) (Nolan and others, 1956, p. 65–68).

OUTLYING MIOGEOSYNCLINAL ROCKS

Fragments of upper Paleozoic miogeosynclinal rocks, mingled with other rocks of varied kinds and ages, crop out in various parts of southern California. In the Mojave Desert are the Orogrande Series and Fairview Valley Formation, mainly carbonates, which contain a few upper Paleozoic fossils. To the south in the San Bernardino Mountains are the Saragossa Quartzite and Furnace Limestone, forming roof pendants in the Mesozoic plutons. Mississippian fossils are found in the Furnace, but a wider age range is suggested by recent studies (Steward and Poole, 1974), which indicate the presence of strata as old as Lower Cambrian. Smaller remnants of similar rocks occur in the San Gabriel Mountains to the west. More enigmatic is the Sur Series of the Coast Ranges, which forms part of the basement of the Santa Lucia Mountains south of Monterey. It is a body of high-grade schists and gneisses, with some large masses of marble. Its age is undetermined, but the series is indicated on the Geologic Map as upper Paleozoic miogeosynclinal rocks (uP), with metamorphic overprint.

EUGEOSYNCLINAL DEPOSITS (uPe)

In north-central Nevada, upper Paleozoic eugeosynclinal deposits closely adjoin the upper Paleozoic miogeosynclinal deposits (Battle Formation, and so forth) already referred to, but they lie in the upper plate of the Golconda thrust that was emplaced during the Sonoma orogeny of late Permian and early Triassic time. The principal rocks are of Permian and possible Pennsylvanian age, but units of Mississippian age occur in outlying areas (Silberling and Roberts, 1962, p. 16–18).

In the Sonoma Range near Winnemucca and some nearby ranges are the Pumpernickel and Havallah

Formations, with a total thickness of more than 15,000 ft (4,500 m). The Pumpernickel is mostly dark bedded chert with minor volcanic rocks, and the Havallah is mainly fine-grained sandstone, with some interbedded chert and argillite. The Havallah contains Wolfcampian or early Leonardian fusulinids; it also contains reworked Atokan fusulinids in the lower part. A few Pennsylvanian conodonts have been recovered from the otherwise barren Pumpernickel Formation, suggesting that it is Pennsylvanian. Recent observations (John M. Stewart, oral commun., 1973) suggest that thick units of Havallah and Pumpernickel lithology are interbedded, and so the two may be not far apart in age.

In the East Range farther west and the Independence Range to the north are the Inskip and Schoonover Formations of chert, argillite, limestone, and volcanic rocks, from both of which a few Mississippian fossils have been collected (Fagan, 1962).

In California, upper Paleozoic eugeosynclinal deposits occur both east and west of the Jurassic and Cretaceous batholith that forms the core of the Sierra Nevada. On the eastern flank near Owens Valley, the Ordovician rocks referred to earlier are succeeded by 7,500 ft (2,300 m) of siliceous hornfels with upper Paleozoic fossils (Rinehart and others, 1959, p. 941–945). On the western flank is the thick mass of the Calaveras Formation, cherts, slates, and volcanics, largely unfossiliferous but generally classed as upper Paleozoic (Clark, 1964). In the Taylorsville area at the north end of the Sierra Nevada is an array of formations, dominantly pyroclastic, composed of dacite, andesite, and basalt (McMath, 1966, p. 179–180). The lower beds contain Mississippian fossils, and the higher are Permian (separately mapped as Pe).

In the southeastern part of the Klamath Mountains, the Devonian sequence is succeeded by the Bragdon Formation, a mass of shale and sandstone, with minor volcanics and some conspicuous layers of conglomerate. It is overlain by the dominantly volcanic Baird Formation. The Bragdon and Baird contain Mississippian and Pennsylvanian fossils. The succeeding rocks, beginning with the McCloud Limestone, are separately mapped as Permian eugeosynclinal deposits (Pe).

In the Blue Mountains uplift of north-central Oregon, upper Paleozoic eugeosynclinal rocks are exposed in small areas beneath the more extensive lower Mesozoic eugeosynclinal rocks. Relations are best shown in the Suplee area at the western end of the uplift, where the rocks are least altered and are abundantly fossiliferous (Merriam and Berthiaume, 1943; Dickinson and Vigrass, 1965, p. 14–16). The lowest unit contains Mississippian and Devonian invertebrates, the middle Pennsylvanian plants, and the

upper early Permian fusulinids and other invertebrates. The lower unit is limestone and sandy limestone; the middle is mudstone, conglomerate, and chert; and the upper is largely volcanic, with irregular fossiliferous limestone lenses. The Paleozoic rocks are structurally unconformable below the Triassic. Much farther northeast, near Baker and Sparta, the Elkhorn Ridge Argillite and Clover Creek Greenstone contain both later Permian fusulinids and Triassic fossils (Bostwick and Koch, 1962) and are shown on the Geologic Map as part of the Triassic and Permian eugeosynclinal deposits (FPe).

In many of the mountain ranges in northern Washington, immediately south of the Canadian border, upper Paleozoic eugeosynclinal deposits, in part metamorphosed, are associated with lower Mesozoic eugeosynclinal deposits but are much disrupted by Mesozoic plutons. They include the Chilliwack Group on the west flank of the northern Cascade Range, the Hozameen Group on the east flank, and still farther east the Anarchist Series. All these units are graywackes, cherts, and volcanics, with occasional lenses of fossiliferous limestone. For the most part, they are of Permian, or Permian and Triassic age, but the Chilliwack Group has yielded Devonian and lower Pennsylvanian as well as Permian fossils (Misch, 1966, p. 115–117).

PALEOZOIC PLUTONIC ROCKS

Plutonic rocks of Paleozoic age are extensive in the crystalline part of the Appalachian Region (New England and Piedmont provinces), and smaller bodies occur in Oklahoma and parts of the Cordilleran Region (fig. 13). They include both felsic (granitic) rocks and mafic rocks. The granitic rocks are divided into four categories according to age—Cambrian, lower Paleozoic, middle Paleozoic, and upper Paleozoic; the mafic rocks are not subdivided, as they form much smaller areas which are not feasible to separate and not all their relative ages are known.

CAMBRIAN GRANITIC ROCKS (Cg)

Plutonic rocks of Cambrian age occur only in a unique tectonic and igneous province that extends northwestward from the Wichita Mountains area of southern Oklahoma into the Rocky Mountains of southern Colorado. Although the rocks are of varied compositions, all are shown as granitic on the Geologic Map.

The most extensive plutonic rock is the Wichita Granite, which crops out along the axis of the Wichita Mountains for 65 mi (97 km). Its Cambrian age is attested by dates of 535 to 550 m.y. obtained by U/Pb,

Rb/Sr, and K/Ar methods (Ham and others, 1964, p. 60–79). It is a floored body which underlies and intrudes the congeneric effusives of the Carlton Rhyolite and which overlies the somewhat older Raggedy Mountain Gabbro, itself a floored intrusive. Extensions of these rocks into surrounding areas are known from drilling, and the Carlton Rhyolite reappears to the east in two small outcrops in the Timbered Hills of the western Arbuckle Mountains. Drilling also indicates that the units mentioned overlie supracrustal rocks not exposed at the surface—the Navajoe Mountain Basalt and the Tillman Metasedimentary Group, the latter a sequence of graywackes at least 15,000 ft (4,500 m) thick that fills a deep trough bordered to the north and south by older Precambrian crystalline rocks. The Wichita Mountains rocks contrast with the Tishomingo Granite and other basement rocks of the eastern Arbuckle Mountains (Yg₁), which have yielded radiometric ages of 1,320–1,400 m.y.

Although of Cambrian age, the plutonic and extrusive rocks of the Wichita Mountains are part of the basement of the Midcontinent Region. Like the older Tishomingo Granite to the east, they are overlain with rough erosion surface by the Upper Cambrian Reagan Sandstone at the base of the cratonic sequence. In the Wichita Mountains, both the granitic rocks and the adjacent lower Paleozoic sedimentary rocks project as peaks and knobs that have been partly exhumed from the surrounding Permian redbeds that formerly buried them.

In Colorado, three small alkalic complexes lie in terranes of Precambrian crystalline rocks, two in the Wet Mountains at the south end of the Front Range and another at Iron Hill north of the San Juan Mountains. These have yielded radiometric ages of 520–580 m.y. and are likewise Cambrian. Probably they lie on a northwestern prolongation of the Wichita Mountains plutonic province (Parker and Sharp, 1970, p. 3; Olson and Marvin, 1971).

LOWER PALEOZOIC GRANITIC ROCKS (Pg₁)

Lower Paleozoic granitic rocks, with ages of about 400 to 500 m.y. (Ordovician and Cambrian), occur throughout the length of the crystalline part of the Appalachians. In New England, they include several different plutonic series.

In the Connecticut Valley of western New Hampshire, five small bodies of the Highlandcroft Plutonic Series intrude the Ordovician rocks, and one of them is truncated and overlain unconformably by the Clough Quartzite, proving its pre-Silurian age. The plutonic rocks were originally quartz monzonite, but they are much sheared and chloritized.

In the Bronson Hill anticlinorium to the east is the

more extensive Oliverian Plutonic Series, which extends southward from New Hampshire into Massachusetts and Connecticut (Naylor, 1968). The Oliverian characteristically is a series of elongate domes, whose foliation is accordant with that of the surrounding and overlying Ammonoosuc Volcanics. The outer part of each body is weakly foliated gneiss, but commonly there is a core of massive granitic rock, which partly crosscuts the mantling gneisses. Both gneiss and granite have yielded Pb/Pb and Rb/Sr ages of 440 to 450 m.y. Present belief is that the gneissic rock was metasomatized from felsic volcanics underlying the Ammonoosuc, into which the more massive core rocks were intruded as magmas. The Oliverian plutonic rocks formed at a deeper crustal level than the Highlandcroft plutonic rocks, in an environment of plastic deformation.

Another group of lower Paleozoic granitic rocks is in southeastern New England, represented by the alkalic Cape Ann, Peabody, and Quincy Granites, north and south of Boston. Formerly it was believed that they were late Paleozoic, an account of their fresh appearance and their apparent affinities with other young alkalic granitic rocks farther northwest, but Pb/Pb determinations on zircons yielded ages of 435 to 452 m.y. Evidently this region was outside of and southeast of the region of Acadian orogeny, where only earlier influences prevailed (Zartman and Marvin, 1971).

In the Piedmont province of the Central and Southern Appalachians, the existence of many bodies of lower Paleozoic granitic rocks is indicated by field relations, supported in many places by radiometric dating. All of them precede the regional metamorphism, which occurred about 380 to 420 m.y. ago (Butler, 1972). Many dates have been obtained by Fullagar (1971) by Rb/Sr whole-rock methods on plutonic rocks in the Piedmont province, and especially in North and South Carolina; these dates were extrapolated on the Geologic Map to related plutons in surrounding areas. The oldest group of plutons has ages of 520 to 595 m.y., hence are Cambrian and Ordovician. One of the plutons, the Farrington igneous complex near Chapel Hill, N.C., intrudes the early Paleozoic rocks of the Carolina Slate Belt and resembles other plutons in the Slate Belt rocks; they are probably congeneric with the volcanic effusives of the belt. Another, the Hatcher complex in central Virginia, is unconformable beneath the Ordovician Arvonian Slate. In Maryland, various small granitic plutons (not shown on the Geologic Map) have ages of about 440 m.y. (Hopson, 1964, p. 199-201).

MIDDLE PALEOZOIC GRANITIC ROCKS (Pg²)

Middle Paleozoic granitic rocks with ages of 350 to 400 m.y. (Devonian) are more plentiful than the lower

Paleozoic granitic rocks, especially in New England. Their principal representative in New England is the New Hampshire Plutonic Series (Billings, 1956, p. 125-129), which forms many plutons in and east of the Bronson Hill anticlinorium, and its extensions southward into Massachusetts, northeastward into Maine as far as Mount Katahdin, and into northeastern Vermont. The earlier members of the sequence are concordant gneissic bodies, probably synorogenic to the Acadian orogeny, such as the Bethlehem Gneiss and Kinsman Quartz Monzonite, which form thick sheets in the lower part of the Littleton Formation. Later members are cross-cutting plutons of binary granite. The later granites of New Hampshire have been dated at 380 m.y., and the Mount Katahdin pluton in Maine at 358 m.y. The coastal plutons of eastern Maine may belong to a distinctly younger, late Devonian plutonic series (Chapman, 1968, p. 386-388); they are nearly circular cross-cutting granitic bodies, embedded in somewhat earlier mafic intrusives.

In the Piedmont province of North and South Carolina granitic plutons with ages of 385 to 415 m.y. are common in the plutonic complex of the Charlotte belt, which adjoins the Carolina Slate Belt on the northwest (Fullagar, 1971, p. 2854-2856).

In the western United States, a single granite body of middle Paleozoic age has been identified in the Beaverhead Range along the eastern border of Idaho. It has been dated by K/Ar methods at 441 m.y. (Scholten and Ramspott, 1968, p. 18-21), but there is some reason to suspect that the granite might actually be Precambrian (Armstrong, 1975, p. 447-448).

UPPER PALEOZOIC GRANITIC ROCKS (Pg³)

Upper Paleozoic granitic rocks, with ages of 250 to 300 m.y. (Pennsylvanian and Permian) occur chiefly in the Piedmont province of the Southern Appalachians.

The only known occurrence in New England is the Narragansett Pier Granite (and the minor associated Westerly Granite) on the south coast of Rhode Island, which intrudes the Pennsylvanian rocks of the Narragansett basin. It has yielded ages of 240 m.y. by K/Ar methods, 259 m.y. by Rb/Sr methods on biotite, and 299 m.y. by Rb/Sr whole-rock methods (Quinn, 1971, p. 51). The White Mountain Plutonic Series of northern New England was formerly assumed to be of late Paleozoic age, but it is now known from radiometric dating to be Jurassic (Jg).

The upper Paleozoic granitic rocks in the Piedmont province occur as discrete plutons in the Carolina Slate Belt and eastern edge of the Charlotte belt in North and South Carolina and Georgia. They are cross-cutting postmetamorphic bodies with ages of about 300 m.y. (Fullagar, 1971, p. 2856-2857). The oldest of the

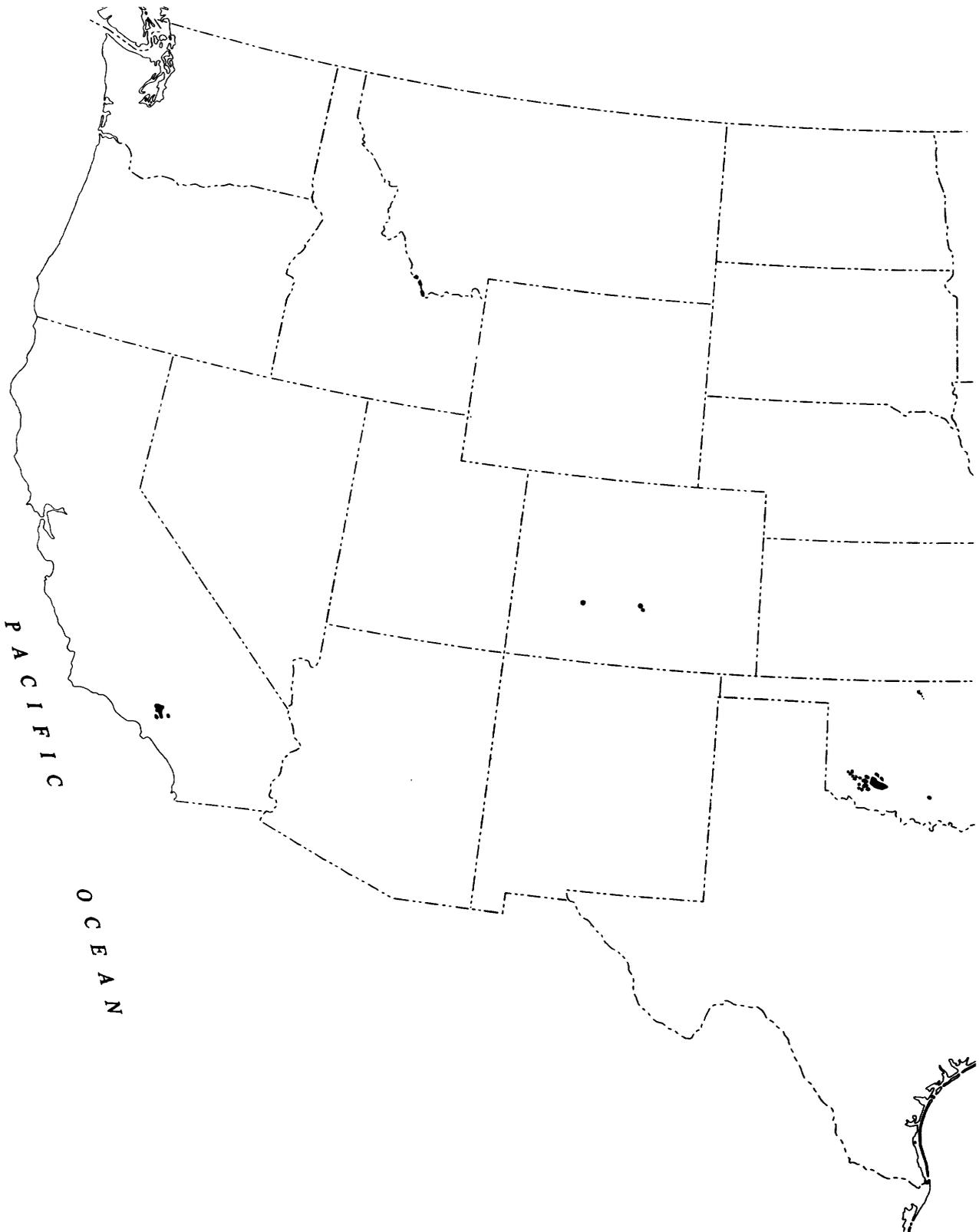


FIGURE 13.—United States, showing areas mapped as Paleozoic plutonic rocks on Geologic Map of United States. Includes units of Cambrian granitic rocks (Pg), lower, middle, and upper Paleozoic granitic rocks (Pg1, Pg2, Pg3), and mafic intrusives (Pmi).

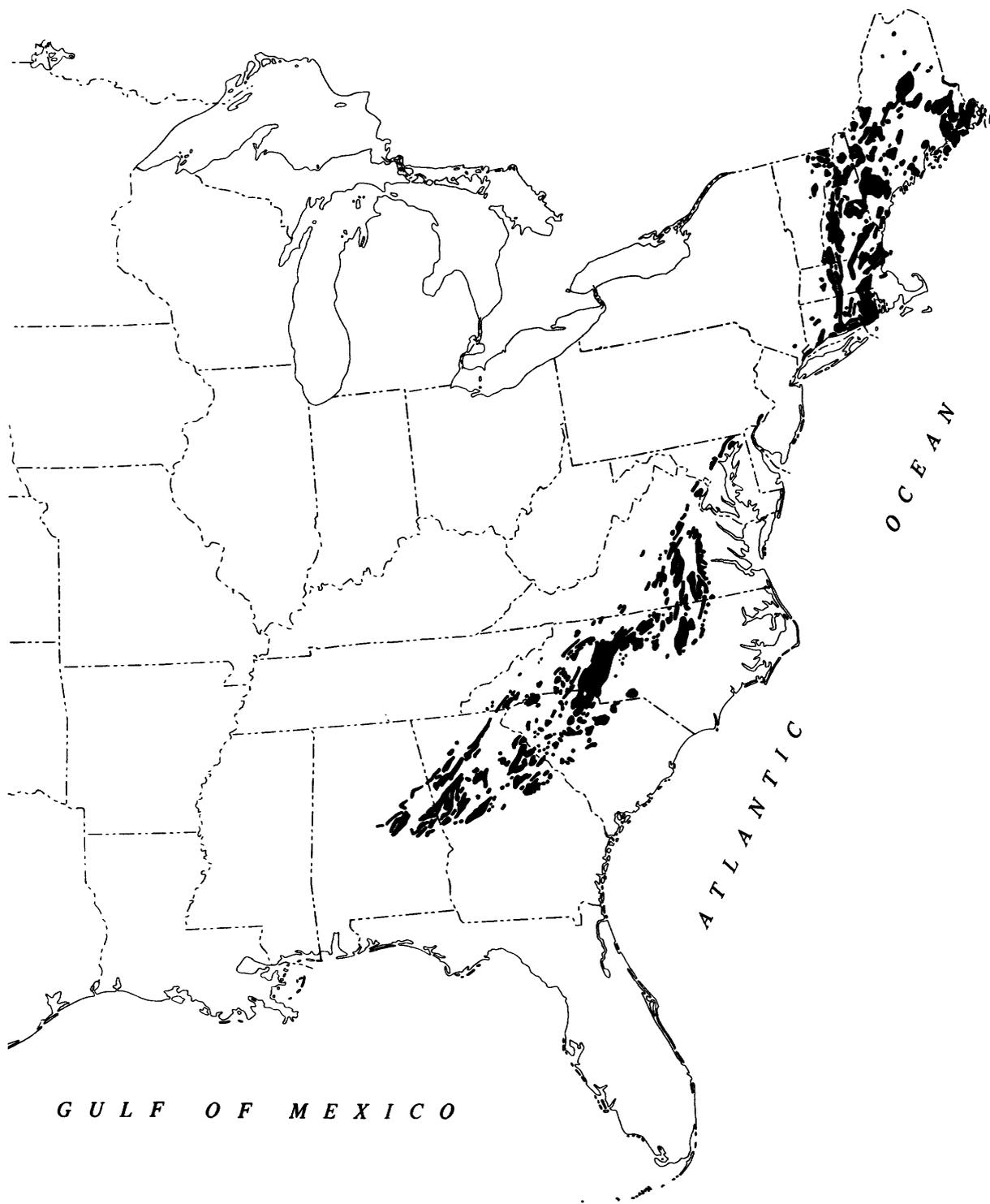


FIGURE 13.—Continued.

group is the Petersburg Granite next to the Coastal Plain overlap in eastern Virginia, which is post-metamorphic like the rest and which has been dated at 330 m.y. by U/Pb determinations on zircon (Wright and others, 1975). (It is shown on the Geologic Map with the middle group of granites, Pg_2). The youngest of the group is the Siloam Granite in the southeastern Piedmont of Georgia, which has yielded a Rb/Sr whole-rock age of 269 m.y. (Jones and Walker, 1973). Northwest of the other plutons, near Atlanta, is the Stone Mountain Granite, which has yielded ages of 280 m.y. by Rb/Sr methods and 294 m.y. by K/Ar methods (Smith and others, 1968; Whitney and Jones, 1974).

The only recorded upper Paleozoic granitic pluton in the western United States is the Mount Lowe Granodiorite of southern California, part of the plutonic complex in the San Gabriel Mountains north of Los Angeles which includes rocks ranging in age from Precambrian to Cretaceous. The Mount Lowe body has a radiometric age of 220 m.y., near the Permian-Triassic boundary (Silver, 1971, p. 194).

PALEOZOIC MAFIC INTRUSIVES ($Pzmi$)

Mafic rocks, mainly gabbro and diorite, intrude the crystalline rocks throughout the length of the Appalachian Region, but in smaller masses than the granitic rocks. They have various Paleozoic ages and various relations to the adjacent granitic rocks and to the regional metamorphism, but they are not subdivided on the Geologic Map because of their small dimensions and because the relations of many of them are not known with certainty. Many of the mafic intrusives are phases of the same plutonic series as the granitic rocks with which they are associated, but some are certainly older.

METAMORPHIC COMPLEXES

The rocks in a few areas in the United States are so strongly metamorphosed and complexly deformed, and have yielded so little indications of their original ages, that they are mapped as metamorphic complexes (m), without any age designation. They form extensive tracts in the Piedmont province of the Southern Appalachians and smaller areas in northern Washington, in the Cascade Range and ranges east of it. Here, instead of classifying the rocks as to age or sequence, they are divided into schist and phyllite (ms), felsic paragneiss and schist (m_1), mafic paragneiss (hornblende and amphibolite) (m_2), migmatite (m_3), and felsic orthogneiss (granite gneiss) (m_4).

The metamorphic complexes of the Piedmont province are probably of Precambrian Z (late Precambrian) and early Cambrian age. In many places they seem

to lie stratigraphically beneath the Cambrian eugeosynclinal deposits (ϵv) of the Carolina Slate Belt and other areas, but other parts seem to be merely the more highly metamorphosed equivalents of the Cambrian rocks. Much more field investigation will be needed to untangle the true relations of the metamorphic complexes and the Cambrian sequence from one area to another. In the Virgilina area along the Virginia-North Carolina border, radiometric dating indicates rocks with ranges in age from 575 m.y. to 740 m.y. that were deformed between 575 and 620 m.y. ago (Glover and Sinha, 1973). The older rocks are more metamorphosed than the younger ones in the Virgilina synclinorium; however, there is no clear break between them, and they are much alike, suggesting that there was no significant depositional break between the Cambrian eugeosynclinal deposits (ϵe) and the adjacent metamorphic complex (m).

The metamorphic complexes in the northern Cascade Range are of undertermined age but appear most likely to be middle and upper Paleozoic. They are older than Paleocene and Cretaceous sediments on the flanks of the range and are probably older than earlier Mesozoic rocks of the area; they are involved in orogenic deformation that preceded the formation of these rocks. A few radiometric ages have been obtained of about 250 m.y., suggesting that the rocks themselves are Permian and older (Misch, 1966, p. 107-115).

The rocks in the western part of the range make up the Shuksan metamorphic suite, with dominant blueschist metamorphism, which overlies less metamorphosed Paleozoic and Mesozoic metamorphic rocks along a major low-angle thrust. The Shuksan is separated from the Skagit metamorphic suite farther east, with greenschist metamorphism, by a major high-angle fault. The Skagit suite includes the Cascade River Schist (ms) and the higher grade migmatized Skagit Gneiss (m_1). Both sets of metamorphic rocks were derived from eugeosynclinal sediments and volcanics but otherwise have little in common; so their original relations to each other are unknown.

East of the Cascade Range is the so-called "Colville batholith," actually a metamorphic complex much like the more famous Shuswap Complex in British Columbia to the north. It consists of a core of paragneiss (m_1), overlain by an outward-dipping body of granitic orthogneiss (m_4) (Fox and Rinehard, 1973).

TRIASSIC AND PERMIAN

EUGEOSYNCLINAL DEPOSITS (ϵ Pe)

A rather diverse assemblage of eugeosynclinal deposits is present in Oregon, California, and Nevada, in

which volcanic rocks are an important component and which contain both Permian and Triassic fossils.

In the Blue and Wallowa Mountains of northeastern Oregon are various units of argillite and greenstone (Elkhorn Ridge Argillite and Clover Creek Greenstone; Gilluly, 1937, p. 14–26), which contain occasional limestone lenses. Some of these lenses contain Leonardian and younger Permian fusulinids, others Triassic fossils (Bostwick and Koch, 1962). A little farther east, along the Snake and Salmon Rivers in western Idaho, are the Seven Devils Volcanics, which likewise contain both Permian and Triassic fossils. All these units are very thick eugeosynclinal accumulations, structurally complex and partly metamorphosed. Whether the Permian and Triassic parts represent continuous sequences, or whether several units are represented, is undetermined. Farther west in the Blue Mountains area, the Triassic sequence is unconformable on the Permian and is grouped with the Jurassic as lower Mesozoic (1M₂e) on the Geologic Map.

Extending the length of the Klamath Mountains in southwestern Oregon and northern California is the wide band of the Western Paleozoic and Triassic belt (Irwin, 1966, p. 21–24; Hotz, 1971, p. 11–13). It forms a structural block tectonically beneath that of the Central Metamorphic belt and tectonically above that of the Western Jurassic belt, and it is entangled with Jurassic granitic plutons and masses of ultramafic rocks. The rocks themselves are fine-grained clastic sediments, bedded cherts, mafic volcanic rocks, and lenses of crystalline limestone. These have been given various local names, such as Applegate Group and Chancelulla Formation, but the limits of such units are uncertain. Permian ammonoids and fusulinids have been collected in some places, and Triassic fossils in others; fossils of older Paleozoic ages have been reported but lack modern verification. Most of the rocks have been subjected to low greenschist-grade metamorphism, but there are some areas of higher grade metamorphic rocks along the eastern side, such as the Stuart Fork Formation (shown by overprint on the Geologic Map). An exceptional area of low-grade schists at Condrey Mountain on the Oregon-California border forms a subcircular window, surrounded by higher grade schists; on the Geologic Map, these rocks are doubtfully correlated with those of the Western Jurassic belt (1M₂e) but may be older.

In northwestern Nevada the Koipato Group of mainly nonmarine rhyolitic and andesitic lavas and associated volcanoclastic rocks unconformably underlies Middle Triassic sediments. It is more than 10,000 ft (3,000 m) thick in its type area in the Humboldt Range, with no base visible, but it thins to disappearance about 40 mi (65 km) to the east, where it overlies

upper Paleozoic eugeosynclinal rocks (Havallah and Pumpnickel Formations, uP₂e) that were deformed by the Sonoma orogeny. Its upper part contains Lower Triassic ammonoids. The Permian fish *Helicoprion* has also been reported, but its occurrence is suspect; Pb/alpha dates of 230 to 290 m.y. (Permian) have been obtained but require verification (Silberling, 1973, p. 349–351).

Farther south is the volcanic Pablo Formation and the associated sedimentary Diablo and Excelsior Formations, which contain Permian and Triassic fossils and are apparently broadly correlative with the Koipato. The Diablo lies unconformably on deformed Cambrian and Ordovician eugeosynclinal rocks (1P₂e) (Silberling and Roberts, 1962, p. 26–28).

TRIASSIC

The Triassic, the lowest system of the Mesozoic Era, is scantily represented on the Geologic Map of the United States. It is separately shown in the Colorado Plateau, in a few of the ranges of the eastern Rocky Mountains, on the western and eastern borders of the Great Plains in New Mexico and Texas, and in a series of fault troughs in the Appalachian Region from New England to South Carolina. In most of the Cordilleran Region, it is merged, where present, with the Jurassic, as a unit of lower Mesozoic (1M₂, 1M₂e). Elsewhere in the United States, and especially in the Central Interior Region, Triassic rocks are missing and were probably never deposited (fig. 14).

The Triassic System is divided into the Lower Middle, and Upper Triassic Series, but these terms are not used on the Geologic Map. The stage terms in the Alps of Europe (Scythian, Anisian, Ladinian, Karnian, Norian, and Rhaetian) are frequently used in discussions of the stratigraphy of the marine Triassic rocks of the west (Reeside and others, 1957, p. 1455–1456).

Most of the rocks shown as Triassic on the Geologic Map are nonmarine and dominantly red colored, but these rocks are not specifically designated as continental deposits. Except in the Colorado Plateau, all of them are Upper Triassic. The Triassic marine deposits of the Cordilleran Region are grouped with Jurassic in the lower Mesozoic unit.

COLORADO PLATEAU

In the Colorado Plateau, the Triassic system is represented by the Moenkopi and Chinle Formations—the first Lower and low Middle Triassic, the second Upper Triassic—with a combined thickness of about 2,000 ft (600 m). At the top is the Glen Canyon Group, also partly of Triassic age, which is shown on the Geologic Map as a unit of Jurassic and Triassic (T₂).

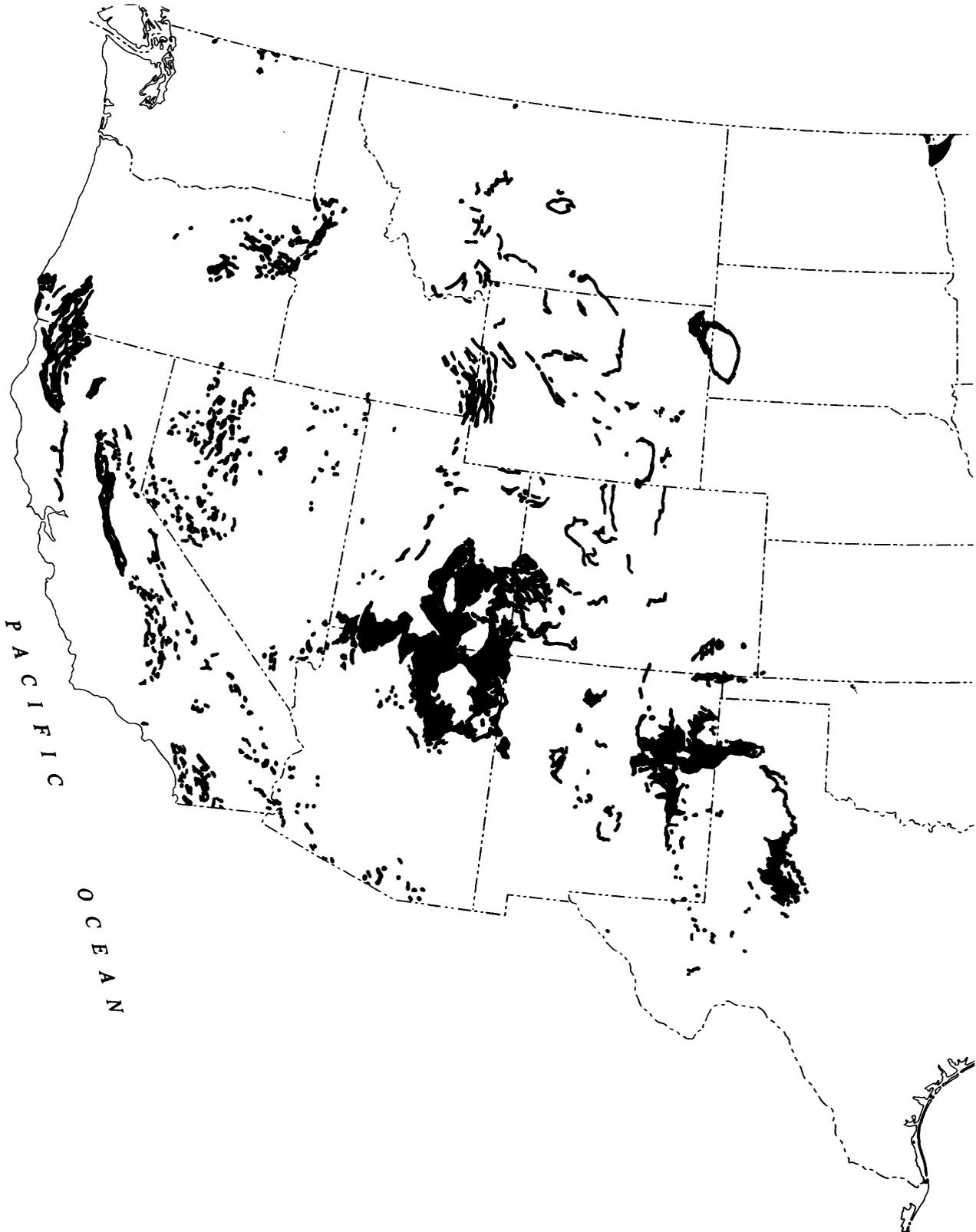


FIGURE 14.—United States, showing areas mapped as lower Mesozoic stratified rocks on Geologic Map of the United States. Includes units of Triassic and Permian eugeosynclinal deposits (T Pe), Triassic (T), Jurassic and Triassic (J T), Jurassic (J), (Jc), and undivided lower Mesozoic (1Mz, 1Me, 1Mv).

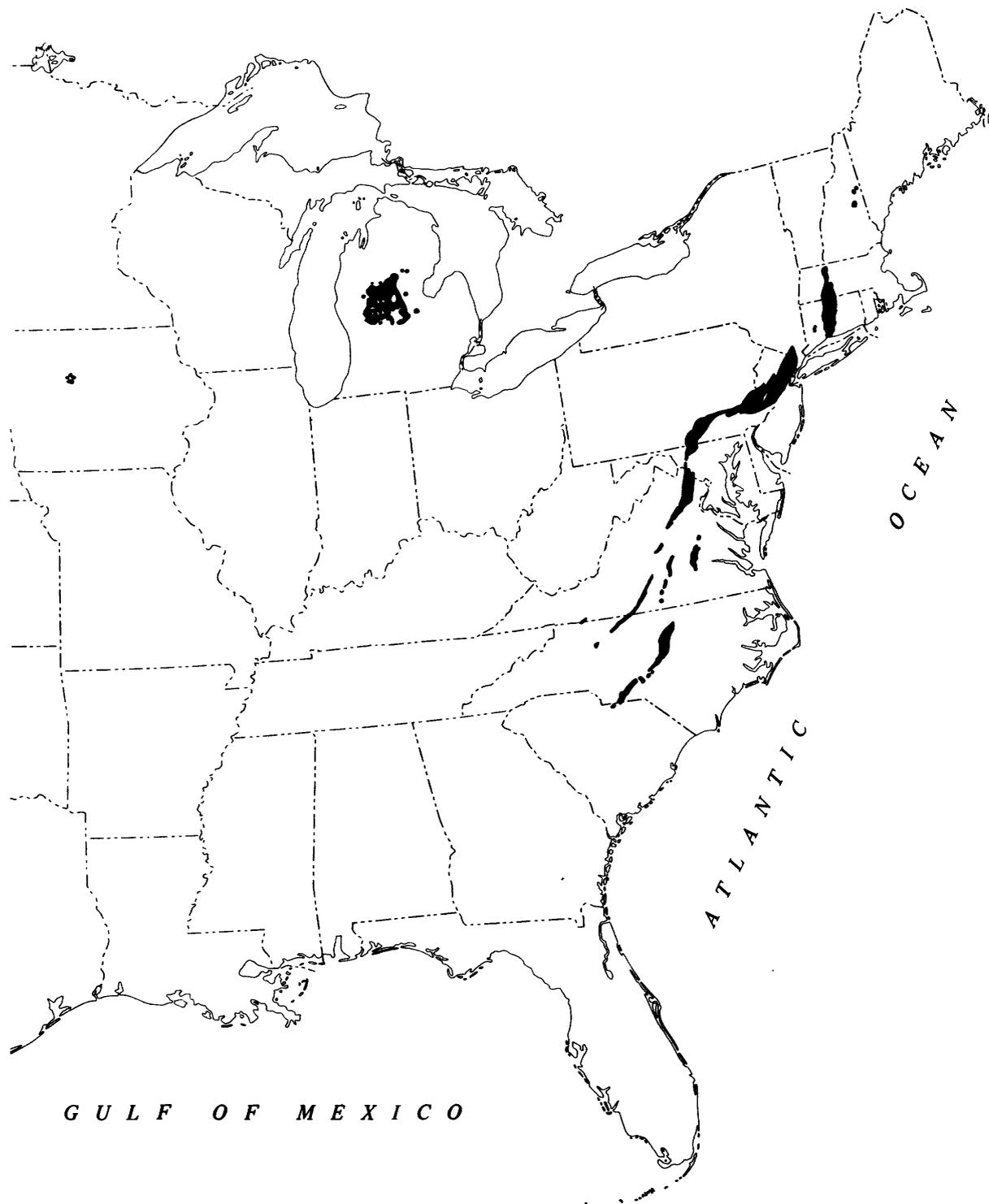


FIGURE 14.—Continued.

The Moenkopi Formation is a red fine-grained evenly bedded deposit, with thin beds of gypsum, and a few of limestone toward the west. Most of it is non-marine, but it grades westward into marine deposits, where it contains the Early Triassic ammonoid *Meekoceras* in the lower part. Elsewhere, the only fossils are vertebrate tracks and bones.

The overlying Chinle Formation is more sandy and brilliantly colored. The persistent Shinarump Conglomerate at the base was laid on the eroded surface of the underlying Moenkopi Formation. The Chinle is entirely nonmarine and contains vertebrates, fossil wood, and a few freshwater invertebrate shells. The Chinle extends eastward beyond the edge of the Moenkopi, into northwestern New Mexico.

GREAT PLAINS

The Dockum Group, another red Upper Triassic unit, forms extensive outcrops in eastern New Mexico and northwestern Texas, on each side of the Tertiary caprock of the Great Plains, and is continuous in the subsurface within the intervening area, where it is the final deposit of the West Texas Permian basin. In the center of the basin, it is about 2,000 ft (600 m) thick, but it is thinner in the outcrops. Various local names have been given to subdivisions, such as Santa Rosa Sandstone in New Mexico and Tecovas and Trujillo Formations in Texas, but they are inconstant and have no general significance (E.D. McKee, in McKee and others, 1959, p. 13-14). The Dockum is entirely non-marine; vertebrates have been found at many places and indicate an approximate correlation with the Chinle Formation farther west.

APPALACHIAN REGION

Rocks of the Upper Triassic Newark Group form a series of faulted troughs in the southeastern part of the Appalachian Region from southern New England to South Carolina. Another fault trough of Newark rocks is in Nova Scotia to the northeast, and rocks like the Newark Group, probably also in fault troughs, have been penetrated by drilling in the Atlantic and Gulf Coastal Plains in Georgia, Alabama, and Florida, and as far west as southern Arkansas (Eagle Mills Formation).

In the Appalachian Region, the Newark rocks lie on the deeply eroded edges of the Paleozoic rocks and the crystalline rocks of the Piedmont. The fault troughs broadly parallel the trends of the earlier structures, however, and in North Carolina, at least, are symmetrically placed on each side of the metamorphic climax in the Piedmont rocks. Commonly, the troughs have

the form of half-grabens, with the beds tilted toward a master fault on one side or the other, which was active during sedimentation. The half-grabens are symmetrically placed; thus, the Connecticut Valley Triassic has its master fault on the east, and the New Jersey-Pennsylvania Triassic, en echelon to the west, has its master fault on the northwest. The Deep River-Wadesboro basin and the Dan River basin in North Carolina have a similar arrangement. In places, there is some evidence that the Triassic deposits were originally continuous between the opposing troughs; in western Connecticut a small downfaulted outlier in the Pomperaug Valley duplicates the sequence in the larger Triassic areas to the east and west. In addition to the master faults, the Triassic rocks are displaced by many other faults that mostly formed after the close of sedimentation. The faults are tensional (taphrogenic) features and were probably produced by rifting associated with the opening of the Atlantic Ocean during Mesozoic time.

Along part of the northwestern border in Pennsylvania, the highest Triassic beds overlap the Paleozoic rocks without surface rupture, but the master fault probably lies beneath and had ceased its activity before the end of Triassic deposition. On the Geologic Map, the fault is represented as continuous.

The rocks of the Newark Group are all nonmarine conglomerates, sandstones, siltstones, and shales, complexly interfingered; many of them are conspicuously red, but some are gray or black. In the Connecticut Valley, the Newark Group is about 12,000 ft (3,700 m) thick, and in the New Jersey-Pennsylvania area at least 20,000 ft (6,000 m); lesser thicknesses occur in the narrower basins farther south.

Most of the coarser beds are arkosic. In New Jersey and Pennsylvania, the first sediments are arkoses derived from crystalline highlands to the southeast, and coarse debris from across the border fault to the northwest appears only above these arkoses. In both the Connecticut Valley and the New Jersey-Pennsylvania area, the deposits next to the border faults are coarse fanglomerates; some fanglomerates in Pennsylvania are formed of carbonate clasts ("Potomac marble"), derived from Paleozoic formations to the northwest. Near the middle, in both the Connecticut Valley and New Jersey-Pennsylvania areas, are dark-gray to black lacustrine shales (for example, the Lockatong Formation), which finger out into the red coarse sediments (D. B. McLaughlin, in Reeside and others, 1957, p. 1491-1494). In the southern basins there are more gray strata, and important beds of coal; the latter have been mined in the Richmond basin, Virginia, and the Deep River basin, North Carolina.

In the Connecticut Valley and in New Jersey, three basalt flows are interbedded in the upper part (F_v). Both here and farther south, the Newark rocks contain thick sills of diabase (F_i), the most prominent of which is the Palisades sill of eastern New Jersey that overlooks the Hudson River and which has been dated radiometrically at 190–200 m.y. (Erikson and Kulp, 1961). In addition, numerous vertical diabase dikes (shown on the Geologic Map) in the Triassic rocks extend far out into the older rocks of the Piedmont province (King, 1971).

Various nonmarine (freshwater or continental) fossils are abundant in parts of the Newark Group, including fishes and plants in the dark shaly beds and vertebrate bones and tracks in the coarser red sediments. They indicate roughly a Late Triassic age, although opinions differ as to precise correlations with standard sections elsewhere.

JURASSIC AND TRIASSIC (J_T)

The designation Jurassic and Triassic (J_T) is used in the western part of the Colorado Plateau for the rocks of the Glen Canyon Group—the Wingate Sandstone, the Moenave and Kayenta Formations, and the Navajo Sandstone (Baker and others, 1936, p. 4–6). Their age is uncertain between Triassic and Jurassic, as fossils are very sparse and relations to better dated rocks in surrounding areas are ambiguous; present judgment is that the Wingate is Upper Triassic and the Navajo Lower Jurassic. However, the group is a cohesive unit, characterized by great cliff-forming sandstones that are a very prominent geomorphic feature in the western part of the plateau, and it has not been subdivided on some of the source maps (Geologic Map of Arizona, 1969); so, it seems best to portray the group on the Geologic Map as a separate unit (J_T). Eastward in Colorado and New Mexico, the group thins out and loses its distinctive character, and thus the separate designation is dropped.

The Glen Canyon Group is commonly 1,000 to 2,000 ft (300–600 m) thick, but the different components vary from place to place; the Navajo Sandstone is thickest toward the west where the Wingate Sandstone is thin or absent, and the Wingate is thickest toward the southeast and extends beyond the featheredge of the Navajo. Both the Wingate and Navajo are massive cliff-forming sandstones, with prominent festoon crossbedding, and are probably largely of eolian origin; the Wingate is characteristically red, and the Navajo white or buff. The intervening Moenave and Kayenta Formations are thinner bedded sandstones that form a topographic bench between the Wingate and Navajo

Sandstones, and the Kayenta contains lenses of mudstone and impure limestone.

JURASSIC

The Jurassic System is represented on the Geologic Map of the United States by marine stratified rocks (J) in the Southern Rocky Mountains, the Colorado Plateau, and the Pacific coastal area of California and Oregon and by continental deposits (Jc) in a few areas in the northern part of the Interior Region. Elsewhere in the Cordilleran Region, it is merged with the Triassic System into a unit of lower Mesozoic (1M_z, 1M_{ze}). In the remainder of the country, and especially in the Interior and Appalachian Regions, Jurassic rocks are absent and were probably never deposited (fig. 14). Jurassic rocks are well developed beneath the Gulf Coastal Plain, where they have been extensively explored by drilling, but none of them are exposed.

The Jurassic is divided into the Lower, Middle, and Upper Jurassic Series. In addition, the western European stage terms (Lias, Bajocian, Callovian, Oxfordian, Kimmeridgian, Portlandian or Tithonian, and others) are commonly used in discussions of Jurassic stratigraphy in North America. None of these subdivisions are shown on the Geologic Map of the United States, because of the narrow outcrop belts.

ROCKY MOUNTAIN REGION

Along the western edge of the Rocky Mountain Region, the Jurassic rocks are miogeosynclinal and marine. The Arapien Shale and evaporites of central Utah are 5,000 to as much as 10,000 ft (1,500–3,000 m) thick, and farther north, from the northern Wasatch Mountains into the thrust belt of southeastern Idaho, a more varied assemblage of formations is about 5,000 ft (1,500 m) thick (mostly shown as 1M_z on the Geologic Map), including the Nugget Sandstone, Twin Creek Limestone, Preuss Sandstone, and Stump Sandstone, which range from Lower Jurassic into Upper Jurassic.

In the Colorado Plateau, the equivalent to the Nugget is probably the Navajo Sandstone, and the higher strata have equivalents in the San Rafael Group, 1,000 to 2,000 ft (300–600 m) thick (Baker and others, 1936, p. 6–9): the Carmel Formation, Entrada Sandstone, Curtis Formation, and Summerville Formations. Most of the group is nonmarine, but the Carmel and Curtis contain fossiliferous marine tongues, by which they can be linked with the miogeosynclinal strata to the northwest. To the north, in the Central and Northern Rocky Mountains, equivalent beds are all marine and form the Sundance Formation in the south and the more comprehensive Ellis Group farther north (mostly shown as 1M_z on the Geologic Map).

Above these deposits throughout the Rocky Mountain Region is the latest Jurassic Morrison Formation, about 250 to 750 ft (75–230 m) thick, nonmarine throughout and probably a flood-plain and lacustrine deposit, and composed largely of variegated mudstones, but with sandstone units locally, especially in the southwest part. It spreads over an area of 655,000 mi² (1,680,000 km²) in the Rocky Mountains and Great Plains to the east and was produced during a remarkable period of quiescence in a region that was tectonically restless both before and after. The Morrison is notable for its abundant remains of dinosaurs and other reptiles, but it also contains fossil freshwater pelecypods and plants.

The Colorado Plateau formations extend eastward across the Southern Rocky Mountains and form narrow bands of outcrop where they are turned up along the eastern flanks of the Front Range and Sangre de Cristo Mountains; they thin to a featheredge in the Great Plains beyond.

Mention should also be made of the Upper Jurassic Malone Formation, exposed in a single area close to the Rio Grande in western Texas (Albritton and Smith, 1965, p. 25–38), which is the sole representative in the United States of the Jurassic miogeosynclinal rocks that are extensive in the Sierra Madre Occidental to the south in Mexico.

PACIFIC COASTAL AREA

Along the western side of the Sacramento Valley in northern California, the Upper Jurassic (Portlandian or Tithonian) Knoxville Formation is exposed for 120 mi (190 km) and forms the base of the "Great Valley sequence" of upper Mesozoic strata. The rocks of this sequence dip homoclinally eastward beneath the valley and are up to 50,000 ft (15,000 m) thick; the Knoxville part alone is 16,000 ft (5,000 m) thick (Bailey and others, 1964, p. 124–130), but it ends abruptly near the 40th parallel at a transverse fault, north of which the Lower Cretaceous rocks (Paskenta) form the base of the sequence. The Knoxville is thin-bedded shale and sandstone (flysch), with some layers of pebbly mudstone, that contains a sparse fauna of *Buchia piochii*, *Inoceramus*, belemnites, and various ammonoids. This fauna is Tithonian, but *Buchia rugosa*, a Kimmeridgian fossil, has recently been discovered in the basal layers (Jones, 1975). Paleocurrents indicate that the Knoxville sediments were derived from the northeast, probably from the Sierra Nevada and Klamath Mountains, whose Jurassic and older rocks had been deformed by the Nevadan orogeny of mid-Jurassic time.

The Knoxville was deposited on an ophiolitic or oceanic crust, now preserved along its western edge as

a great sheet of serpentinite, followed by diabase, pillow lava, and radiolarian chert, which pass upward into the normal Knoxville sequence (Bailey and others, 1970). The serpentinite and overlying Knoxville are thrust westward over the partly coeval Franciscan Formation.

Other Knoxville-type Upper Jurassic rocks crop out in places at the base of the Great Valley sequence farther south along the edge of the valley, but they are too small to separate from the Cretaceous on the Geologic Map.

Jurassic rocks are also shown on the Geologic Map in the structurally complex coastal area of southwestern Oregon, where they are juxtaposed against other Mesozoic rocks—Upper and Lower Cretaceous (uK, lK), the Dothan Formation (Franciscan equivalent, uMe), the Galice Formation (lMe), and masses of serpentinite. The largest Jurassic unit is the Otter Point Formation (Koch, 1966, p. 36–43; Coleman, 1972, p. 12–14), a thick graywacke-shale unit, including much volcanic material (pillow lavas and pyroclastic debris), that contains *Buchia piochii* and other Tithonian fossils.

CONTINENTAL DEPOSITS (Jc)

In the northern part of the Interior Region, the Paleozoic rocks are capped in places by red continental deposits, which palynological studies demonstrate are of Early Jurassic age (Cross, 1967), although they have erroneously been assigned to the Pennsylvanian or the Permian System in the past. The largest area is in the center of the Michigan basin, where 300 to 400 ft (90–120 m) of red shale and sandstone, with minor gypsum, overlie the Pennsylvanian sequence (Cohee, 1965, p. 220). The Fort Dodge Gypsum and associated redbeds similarly overlie Pennsylvanian rocks in a smaller area in north-central Iowa. Another area of Jurassic continental deposits is mapped in northwestern Minnesota next to the Canadian border but is apparently known mainly from drilling beneath the glacial cover; it is the south end of an extensive belt in Manitoba, lying between the Cretaceous sequence on the west and the Paleozoic on the east.

LOWER MESOZOIC

In extensive areas of the Cordilleran Region, the Triassic and Jurassic rocks are combined on the Geologic Map into a unit of lower Mesozoic, which includes marine stratified rocks (lMz), eugeosynclinal deposits (lMe), and volcanic rocks (lMzv).

MARINE STRATIFIED ROCKS (lMz)

The lower Mesozoic marine stratified rocks are relatively thin cratonic deposits in Wyoming and Montana

but are thicker miogeosynclinal deposits in southeastern Idaho and westward in the Great Basin of Utah and Nevada. They also change westward from dominantly continental deposits to dominantly marine deposits.

The cratonic deposits, as exposed on the flanks of the mountain uplifts, are 500 to 1,500 ft (150–500 m) thick and comprise the redbeds of the Chugwater Formation (Upper Triassic) below, followed by the marine Sundance or Ellis Formations, and topped by the continental Morrison Formation (Jurassic). The Triassic redbeds wedge out northward in southern Montana, and only the Jurassic units persist beyond.

In the miogeosynclinal belt of southeastern Idaho, the Triassic sequence thickens to nearly 7,000 ft (2,100 m) and the Jurassic to 5,000 ft (1,500 m), and there is a more complex array of formations—the Dinwoody, Thaynes, and Ankareh Formations in the Triassic, and the Nugget Sandstone, Twin Creek Limestone, and Preuss and Stump Sandstones in the Jurassic. The Idaho Triassic section is notable for containing the thickest and most complete sequence of Lower Triassic in the world, and it contains ammonoids at many levels, including *Meekoceras* (Kummel, 1954, p. 165). The basal Dinwoody Formation lies with nearly parallel bedding and no indication of erosion on the Permian Phosphoria Formation, although separated from it by a considerable hiatus. The thicker, overlying Thaynes Formation is dominantly limestone, although with silty and sandy members, and intertongues with redbeds toward the craton. Jurassic rocks do not extend beyond western Utah, but the Triassic System is well represented in northeastern Nevada (Elko County), where the sequence is mostly limestone and as much as 3,000 ft (900 m) thick (Clark, 1957, p. 2200–2209).

A quite different set of lower Mesozoic miogeosynclinal deposits occurs in west-central and southwestern Nevada. It is separated from those just described by a 100-mile (160 km) gap, which was probably a land barrier. In the Sonoma Range and elsewhere near Winnemucca in north-central Nevada are two sequences, the Augusta to the east and the Winnemucca to the west, that were juxtaposed by moderate westward thrusting during later Mesozoic time (Silberling and Roberts, 1962, p. 19–25). Both lie in part on the Koipato Formation (KPe), but they have no formations in common. The Augusta sequence was deposited nearer the shore to the east, and its lower part passes eastward into conglomerates and coarse clastics (China Mountain and Panther Canyon Formations); much of the rest is limestone. Where fully developed, the sequence is about 8,000 ft (2,400 m) thick. The Winnemucca sequence formed farther from shore and passes westward into deep-water turbidites and even-

tually into eugeosynclinal deposits. In its miogeosynclinal phase to the east, its lower part (Prida and Natchez Pass Formations) is largely limestone, but the higher parts are shaly and sandy; the Winnemucca sequence reaches a thickness of 10,000 ft (3,000 m). The Augusta sequence is of Middle and Upper Triassic age, but the Winnemucca sequence includes Lower Jurassic rocks at the top.

About 60 mi (100 km) south of the exposures of these sequences is the Luning sequence of latest Triassic and Early to Middle Jurassic age (Silberling and Roberts, 1962, p. 28–33), which also was deposited west of a shoreline. The greater part of the sequence is the Luning Formation, as much as 8,000 ft (2,500 m) thick, largely of carbonate rocks, including coral reefs. Later on, local folding and thrusting occurred, and so the coarse clastics and fanglomerates of the Dunlap Formation at the top rest on different older parts of the sequence from place to place, and even on pre-Triassic rocks.

EUGEOSYNCLINAL DEPOSITS (IMe)

Small areas of lower Mesozoic rocks, intruded by Mesozoic granitic rocks, occur in western Nevada and to the west in the Sierra Nevada of California. They change westward from miogeosynclinal to eugeosynclinal deposits; on the Geologic Map the line of separation is made between unit J₁F (shale, mudstone, siltstone, and sandstone) and unit J₂F (shale, sandstone, volcanogenic clastic rocks, andesite, and rhyolite) as represented on the compilation for the new Geologic Map of Nevada.

Lower Mesozoic eugeosynclinal deposits, again associated with Mesozoic granitic rocks, are more extensive in the Sierra Nevada. In the eastern Sierra the thickest sequence is in the Ritter Range roof pendant west of the head of Owens Valley, where there are 30,000 ft (9,000 m) of intermediate to felsic pyroclastic rocks (Rinehart and others, 1959, p. 945). Early Jurassic fossils occur about a third of the way up in the sequence, and so there is a possibility that unrecognized Triassic and later Jurassic rocks may be present.

The largest area of lower Mesozoic eugeosynclinal deposits in the Sierra Nevada, however, is in the western foothills from the Mother Lode belt westward, where there is about 15,000 ft (4,500 m) of volcanic rocks and volcanoclastic sediments (Clark, 1964, p. 6–8). These include the “Mariposa Slate” of the Gold Belt folios, as well as “porphyrite,” “diabase,” and “amphibolite” that were once considered to be intrusive but are now known to be supracrustal volcanic deposits. (They were erroneously grouped with the Sierra Nevada granitic rocks on the Geologic Map of

the United States of 1932.) The rocks have been subjected to low-grade greenschist metamorphism, but fossils occur at various places which indicate ages ranging from Middle to Late Jurassic (Bajocian to Kimmeridgian). The base of the sequence is generally juxtaposed against serpentinite which was probably original oceanic crust, and no Triassic is present. The sequence is also largely older than the Knoxville Formation at the base of the Great Valley sequence to the west, which is largely Portlandian (=Tithonian), although it includes some Kimmeridgian at the base (Jones, 1975).

Modern work indicates that these Jurassic rocks actually consist of several sequences of unlike formations. The eastern sequence includes the original Mariposa Formation at the top, of slate, tuff, and graywacke, underlain by the Logtown Ridge Formation of andesitic volcanic breccia, pillow lava, tuff, and sandstone. The western sequence begins with the Gopher Ridge Volcanics of basaltic, andesitic, and rhyolitic pyroclastic rocks and lavas, followed by the Salt Spring Slate (possibly equivalent to the Mariposa), the Merced Falls Slate, and the Copper Hill Volcanics which resemble those of the Gopher Ridge. Both sequences are island-arc deposits which originally formed far apart, but which are now closely adjoined as a result of faulting and subduction (Schweickert and Cowan, 1975, p. 1329-1331). Toward the north the two sequences are separated by the 20-mile (32-km) Smartville terrane, which is ophiolitic ocean floor facies, with pillow basalts underlain by sheeted dike complexes and intrusive gabbro. This terrane wedges out southward between the sequences, leaving a narrow belt of melange containing a great variety of tectonic blocks, including Permian fusulinid-bearing limestone of unknown original provenance (Duffield and Sharp, 1975).

In the southern part of the Sierra Nevada, the prevailing granitic rocks contain many small roof pendants of supracrustal rocks, most of which are undated but all of which are shown on the Geologic Map as lower Mesozoic eugeosynclinal deposits (1M_{ce}).

In the Taylorsville area at the north end of the Sierra Nevada, the Triassic System is represented by the Hosselkus Limestone and Swearinger Slate, two relatively thin nonvolcanic abundantly fossiliferous units of Late Triassic age. They are followed on Mount Jura by a 13,000-ft (4,000-m) sequence of clastic and volcanoclastic rocks, subdivided into many units whose fossils indicate a nearly complete sequence from base to top of the Jurassic System (McMath, 1966, p. 181-182). In a somewhat similar sequence along the strike to the north in the easternmost belt of the Klamath Mountains, 9,000 ft (2,700 m) of Triassic rocks overlie

the Permian sequence and are succeeded by 7,000 ft (2,100 m) of Jurassic rocks.

A very different sequence of lower Mesozoic eugeosynclinal deposits forms the Western Jurassic belt of the Klamath Mountains for its entire length, from southwestern Oregon into northern California (Irwin, 1966, p. 24-25; Hotz, 1971, p. 13-14). It is faulted against the Western Paleozoic and Triassic belt (WPe) on the east and the Franciscan Formation (=Dothan Formation) on the west. Its rocks constitute the Galice Formation, volcanic below and clastic above, that is as much as 15,000 ft (4,600 m) thick and that is dated by fossils as of Oxfordian and Kimmeridgian age; it has commonly been compared with the Mariposa Formation of the western Sierra Nevada.

Northeast of the Klamath Mountains, in the Blue Mountains uplift of north-central Oregon, lower Mesozoic and Paleozoic rocks are again exposed. Those in the eastern part are mainly mapped as Triassic and Permian eugeosynclinal deposits (E_{Pe}), but the stratigraphy in the western part is clearer and the rocks less metamorphosed; a typical sequence occurs in the Suplee-Izee area (1M_{ce}) (Dickinson and Vigrass, 1965, p. 17-67). Lying unconformably on the Paleozoic is a sequence about 25,000 ft (7,600 m) thick of Late Triassic (Karnian) to early Late Jurassic (Callovian) age, the different parts themselves separated by angular unconformities. Its sediments are largely argillites and siltstones, with interbedded sandstones and minor limestones, but lavas and volcanoclastic rocks occur in nearly all the units and dominate the upper third of the sequence.

Far to the south, in the Peninsular Range of southern California, small to large bodies of supracrustal rocks are invaded by the Cretaceous Peninsular batholith. Most of these rocks are lower Mesozoic, although Paleozoic (uPe) rocks may occur in the San Jacinto Range to the east. The rocks are least metamorphosed and the sequence is plainest at the northwestern end, in the Santa Ana Mountains (Yerkes and others, 1965, p. 23). Below is the Bedford Canyon Formation, at least 20,000 ft (6,000 m) thick of argillite and slate, with some sandstone and limestone; it is overlain with angular unconformity by the Santiago Peak Volcanics, several thousand feet thick. Fossils in the Bedford Canyon indicate an early Late Jurassic (mainly Callovian) age (Imlay, 1962, p. 98-100). (Similar fossils occur in the Santa Monica Slate, exposed in an inlier northwest of the Los Angeles basin.) The Santiago Peak Volcanics have not been dated; they are overlain unconformably by Upper Cretaceous rocks and may be of latest Jurassic or even Early Cretaceous age, like similar rocks farther south in Baja California. The Julian Schist in the core of the Penin-

sular Range has not been dated, but it may be a metamorphic phase of these formations.

In the Mojave Desert region, between the Peninsular Range and the Sierra Nevada, many small areas are represented on the Geologic Map as lower Mesozoic eugeosynclinal deposits (1M_ze). They include the Sidewinder Volcanics and Ord Mountain Group, of andesite and rhyolite flows and volcanoclastic rocks, generally believed to be Triassic. In the Clark Mountains farther east, however, volcanics overlie the Jurassic Aztec Sandstone. Similar rocks of less certain ages occur southeastward as far as the Colorado River and are classed as lower Mesozoic on the Geologic Map. In southwestern Arizona the State Map shows units of "Mesozoic gneiss" and "Mesozoic schist"; for purposes of the Geologic Map, the first is assumed to be Precambrian reworked by Mesozoic orogenies and the second to be lower Mesozoic eugeosynclinal deposits.

VOLCANIC ROCKS (1M_zv)

Terrestrial volcanic rocks (as contrasted with the eugeosynclinal volcanics already discussed) occur in several small areas, unrelated to each other, in widely scattered parts of the United States.

The Moat Volcanics of New Hampshire (Billings, 1956, p. 35-37) are associated with and probably congeneric with the Jurassic White Mountain Plutonic Series and are preserved in downdropped blocks surrounded by ring dikes of the plutonic rocks. They consist of rhyolite flows and breccias up to 11,000 ft (3,300 m) thick and lie unconformably on Paleozoic rocks that were deformed and metamorphosed during the Acadian orogeny. They contrast surprisingly with the Upper Triassic sedimentary and volcanic rocks of the Newark Group not far to the south in New England.

In the northeastern part of the Cortez Range in north-central Nevada is the Pony Trail Group of volcanic wacke, tuff, and rhyolite flows about 10,000 ft (3,000 m) thick (Muffler, 1964, p. 20-39). It is not in contact with the adjacent Paleozoic rocks, but it is overlain in part by the Cretaceous Newark Canyon Formation (Kc) and is intruded by Jurassic granitic plutons. These volcanic rocks contrast with the lower Mesozoic miogeosynclinal rocks not far to the east and west but probably accumulated on the land barrier which separated the two groups of miogeosynclinal deposits.

In some of the ranges close to the Mexican border in southern Arizona is another assemblage of lower Mesozoic volcanic rocks (Hayes and Drewes, 1968, p. 51-54), which lie unconformably on Paleozoic rocks and are overlain unconformably by the Lower Cretaceous Bisbee Group. They consist of a lower volcanic unit as much as 10,000 ft (3,000 m) thick of rhyodacite

and andesite flows and tuffs, a middle redbed unit about 2,000 ft (600 m) thick, and an upper volcanic unit about 7,000 ft (2,100 m) thick of silicic flows and tuffs. Fossils are rare and not diagnostic, but Pb/alpha and K/Ar determinations indicate that the sequence ranges in age from Early Triassic to Early Jurassic. The volcanics are, further, intruded by Jurassic granitic rocks that have yielded a Pb/alpha date of 184 m.y.

CRETACEOUS

In terms of the Geologic Map of the United States, the Cretaceous System, or uppermost division of the Mesozoic, by far overshadows the Jurassic and Triassic Systems, as well as many of the Paleozoic systems, not only in the wide extent of its exposures but in the variety and complexity of its formations.

The Cretaceous sequence forms a nearly continuous band of outcrop in the Atlantic and Gulf Coastal Plains and expands in Texas into the hill and plateau country to the northwest (fig. 15). It is even more extensive in the central and northern Great Plains and westward in the Rocky Mountains. Other outcrops occur in the Pacific coastal area through California into southwestern Oregon. Most of the Cretaceous rocks so represented are marine, but the marine deposits in the Rocky Mountains change westward in the Great Basin into continental deposits (Kc).

The Cretaceous is divided into the Lower Cretaceous and Upper Cretaceous Series (1K, uK), whose local representatives in the Gulf Coastal Plain are called the Comanche and Gulf Series. The Lower Cretaceous comprises the Neocomian, Aptian, and Albian Stages, and the Upper Cretaceous the Cenomanian, Turonian, Coniacian, Santonian, Campanian, and Maestrichtian Stages of the European classification.

LOWER CRETACEOUS

TEXAS

The Comanche Series of the Lower Cretaceous is mainly of Albian age but may include some Aptian rocks at the base. The remainder of the Aptian stage, and the Neocomian, are unrepresented in Texas, although they are well displayed in Mexico to the south, where they have been called the Coahuila Series (Im-lay, 1944, p. 1005-1007). The Comanche Series departs from the European classification by including some Cenomanian units at the top (Del Rio Clay and Buda Limestone); the discrepancy is not fundamental, as these are very thin units.

The Comanche Series is divided into the Trinity, Fredericksburg, and Washita Groups (1K₁, 1K₂, 1K₃), which are separately represented on the Geologic Map in the broad outcrop area that extends across central

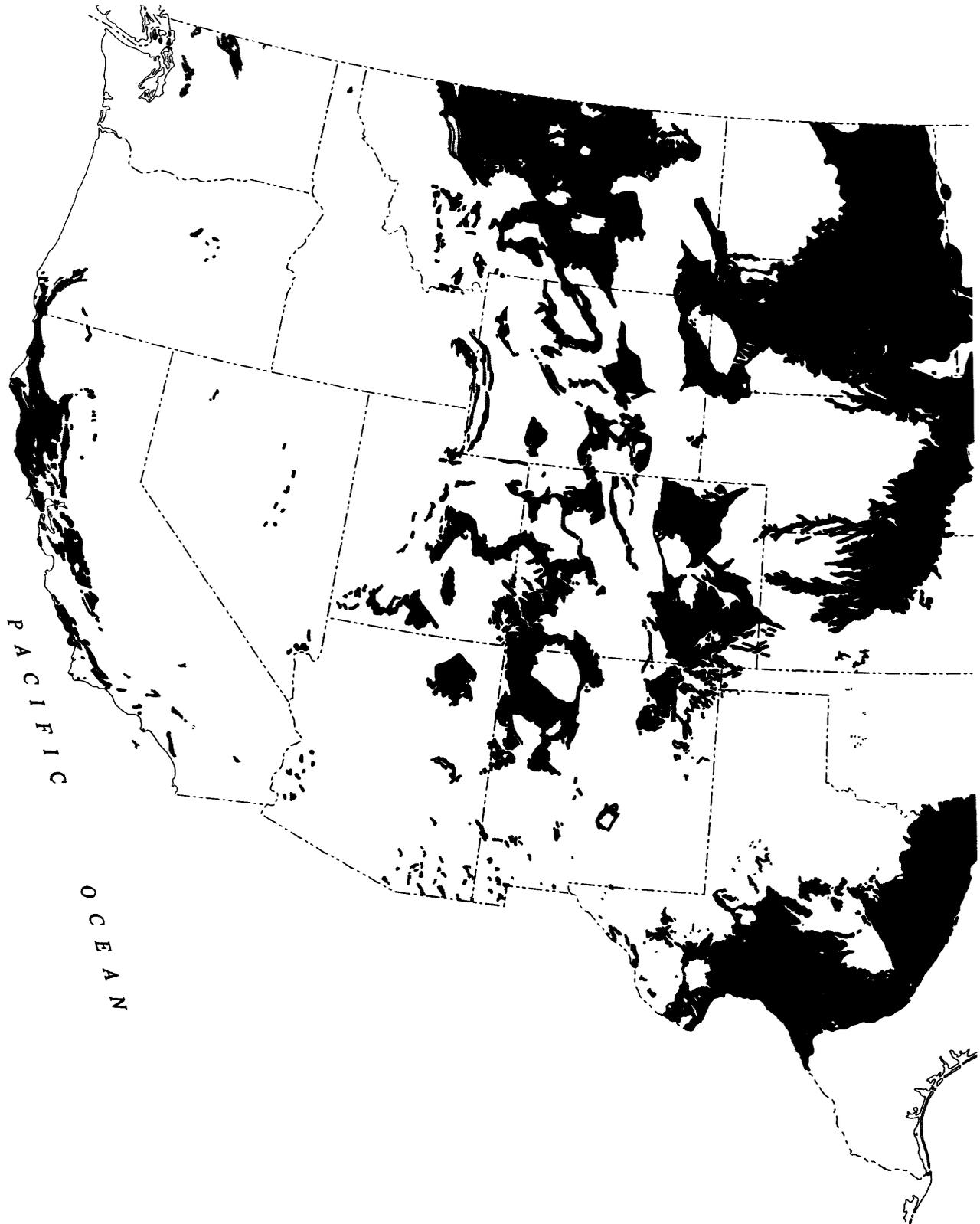


FIGURE 15.—The United States, showing areas mapped as Cretaceous stratified rocks on the Geologic Map of the United States; Lower and Upper Cretaceous are separately shaded. Includes units of Lower Cretaceous (1K, 1K1, 1K2, uM e) and of Upper Cretaceous (uK, uK1, uK2, uK3, uK4, Kc, Ke, Kv) age.

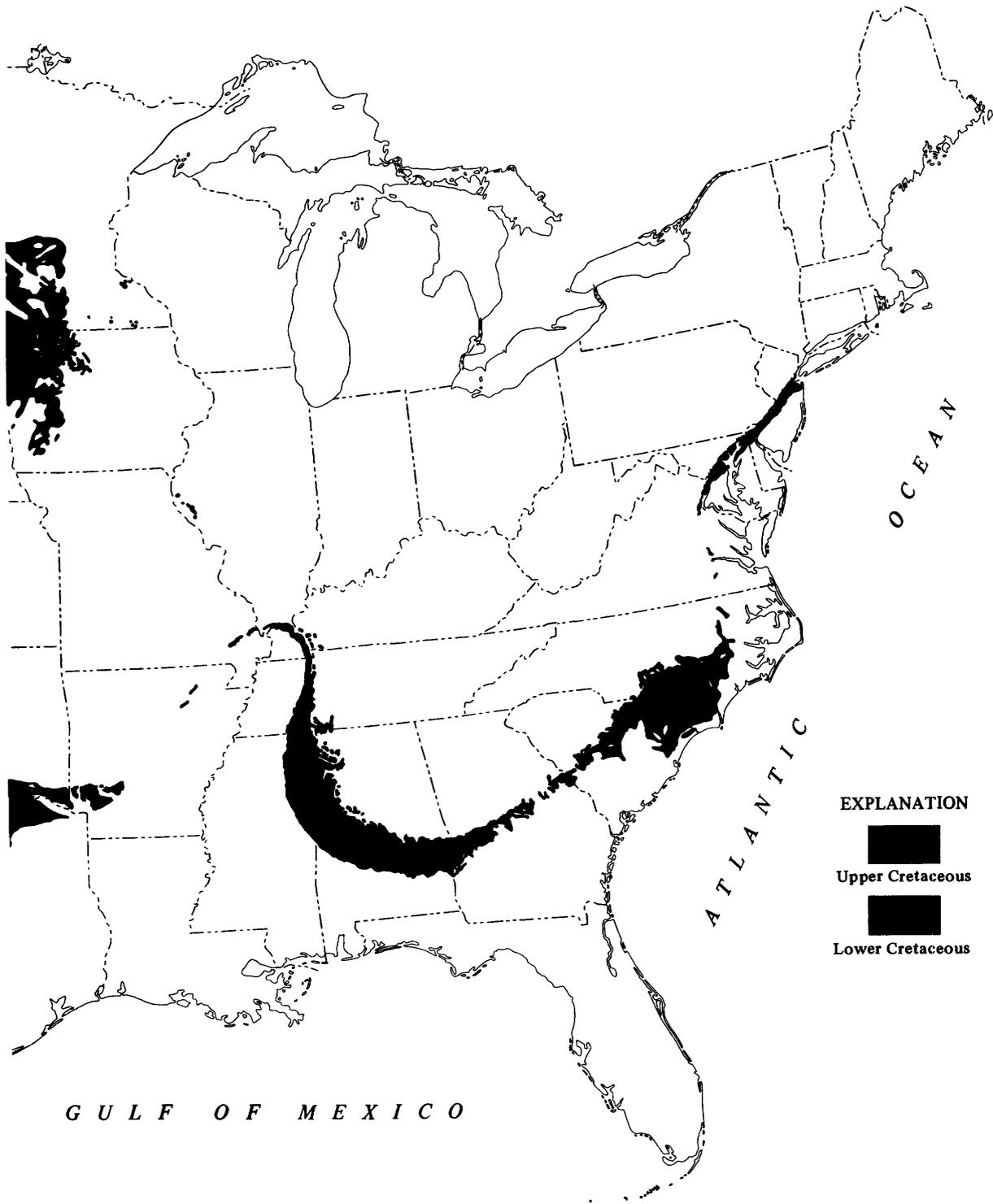


FIGURE 15.—Continued.

and northern Texas. (For a summary of the Comanche Series, see the useful but now somewhat outdated presentation by Adkins (1932, p. 272-400).) In west Texas, where the outcrop bands are narrow and the structure more complex, the separation is not made, nor is it made in the small outlying areas of the Comanche Series in southern Arizona, Oklahoma, and southern Kansas.

The Trinity Group ($1K_1$) is an irregular basal deposit that lies on the eroded surface of Paleozoic and Triassic rocks. Where best developed near Austin, it is 800 ft (240 m) or more thick and consists of the Travis Peak Formation below of sands, clays, and thin limestones and the overlying Glen Rose Formation of ledge-making limestones alternating with softer marls. Toward the north and west, the group thins and finally disappears; sandstone tongues increase in prominence and finally dominate altogether. The Fredericksburg Group ($1K_2$), 500 ft (150 m) or more thick, contains the thick widespread rudistid-bearing Edwards Limestone, with the more marly Walnut Clay and Comanche Peak Limestone below and the Kiamichi Formation above. The Washita Group ($1K_3$) in north Texas consists of marls and clays with thin interbedded limestones, divided into an array of formations. Southward toward Austin it thins into a more condensed sequence, the Georgetown Limestone, with the thin well-marked Del Rio Clay and Buda Limestone at the top. The units in western Texas are similar but have some local variations.

In a broad area from Austin to the Pecos River and beyond, the Comanche Series lies nearly flat and forms the Edwards Plateau. Much of the surface of the plateau is not formed of the Edwards Limestone, however, but of similar limestones of the Washita Group, and lower formations are penetrated only in canyons along the edges. The extent of the Washita is much greater than has been shown on previous maps (Geologic Map of United States of 1932; Geologic Map of Texas of 1937), where the base of the Washita had been placed erroneously 100 to 200 ft (30-60 m) too high, resulting in a notable difference in map pattern in this flat-lying terrane.

In the southern part of the plateau, the simple stratigraphy farther north breaks down, and the Fredericksburg and Washita Groups merge into a massive reef deposit, the Devils River Limestone (Smith, 1970, p. 43-44). (On the Geologic Map, this facies change is ignored and the Fredericksburg-Washita boundary is sketched arbitrarily through the deposit.) The Devils River Limestone reef is the only surface exposure in the United States of a regional feature—a south-facing shelf break and barrier reef that extends far eastward in the subsurface beneath the Gulf Coastal Plain and

at the surface southwestward across the Rio Grande into Mexico.

From northern Texas, the outcrop belt of the Comanche Series extends eastward across southern Oklahoma into southwestern Arkansas, but its top is progressively truncated by the unconformity at the base of the Upper Cretaceous Woodbine Sand (uK_1) until none remains, although it continues in full development in the subsurface to the south.

Westward from western Texas, small outcrops of Comanche Series in southern New Mexico and in southeastern Arizona, where it is represented by the Bisbee Group, are as much as 10,000 ft (3,000 m) thick (Hayes and Drewes, 1968, p. 55-56); they are typically developed in the Mule Mountains near Bisbee. Here, the middle part is the Mural Limestone, with Trinity and possibly Fredericksburg marine fossils, and the Morita Formation below and Cintura Formation above are pinkish sandstones and siltstones, largely terrestrial. The Glance Conglomerate at the base lies on a rough surface eroded on the Paleozoic rocks and the lower Mesozoic volcanics and likewise contains some interbedded lava. Northwestward, the Mural Limestone wedges out, and the terrestrial deposits alone remain.

North of Texas, small outliers of Comanche rocks are scattered over the Permian rocks in western Oklahoma, and a larger remnant occurs at the edge of the Great Plains in southern Kansas, where the series is represented by the Cheyenne Sandstone and Kiowa Shale (Merriam, 1963, p. 60-61). The latter contains thin limestones and shell beds whose fossils are of Washita age, the older units having disappeared by overlap. Farther north, the Comanche rocks largely wedge out, although their thinned equivalents may be represented in the Dakota Sandstone (uK_1).

ATLANTIC COASTAL PLAIN

East of Arkansas, Lower Cretaceous rocks are missing for a long distance at the edge of the Coastal Plain, and their next appearance is in northern Virginia, Maryland, and New Jersey, where they form the Potomac Group, typically developed near Washington, D.C. (Spangler and Peterson, 1950, p. 62-69). The Potomac Group consists of terrestrial sandstones, sandy shales, and clays, with local beds of gravel and lignite; it is as much as 800 ft (240 m) thick and has been divided into the Patuxent, Arundel, and Patapsco Formations. Equivalents in New Jersey are in the Raritan Formation which is partly Upper Cretaceous. Some of the nonmarine Tuscaloosa Formation of North Carolina, generally classed as Upper Cretaceous, may also be of Potomac age. The Potomac group contains

fossil plants at many levels, and the Arundel Formation contains reptiles like those of the Morrison Formation of the Rocky Mountains. According to commonly accepted correlations, the group is of Neocomian age at the base but extends into the Aptian Stage.

ROCKY MOUNTAINS

Lower Cretaceous rocks, mostly a few hundred feet (60–100 m) thick, are extensive in the Rocky Mountains and in the subsurface in the Great Plains to the east, but on the Geologic Map they are for the most part merged with the Dakota Group (uK₁) of the Upper Cretaceous on the Geologic Map. The Dakota itself is a problematical unit: In its original area in eastern Nebraska it is all Upper Cretaceous; in other areas the so-called Dakota is Lower Cretaceous; in still others the Dakota Group includes formations of both ages. In the Black Hills of South Dakota and Wyoming, for example, rocks mapped as uK₁ include the Inyan Kara Group (Lakota Sandstone, Fuson Shale, and Fall River Sandstone, the latter the Dakota Sandstone of original reports), the Skull Creek Shale, Newcastle Sandstone, and Mowry Shale, the last of late Albian age—in other words, all Lower Cretaceous. In northeastern New Mexico and southwestern Colorado, the thin marine Purgatoire Formation, a tongue of the Comanche Series, is included in uK₁. Similar combinations, or others with varied terminologies, occur in other areas.

On the Geologic Map, the only Lower Cretaceous rocks represented as such are shown in the west and northwest, where the Lower Cretaceous rocks are thicker and not involved in the "Dakota problem."

In the thrust belt of southeastern Idaho and western Wyoming, the Lower Cretaceous (lK) includes the Gannett Group, 3,500 to 5,000 ft (1,000–1,500 m) thick (Eyer, 1969); the Bear River Formation, 500 ft (150 m) thick; and the Wayan Formation, 3,000–4,000 ft (900–1,200 m) thick, which range in age from Neocomian through Albian. Only the thin Bear River Formation contains marine elements; the Gannett and Wayan are continental tectonic deposits related to the growth of the thrust belt, with much conglomerate and coarse-grained sandstone and interbedded red and purple mudstone. Pauses in tectonic activity during deposition of the Gannett Group are indicated by two units of lacustrine limestone.

In west-central Montana the Lower Cretaceous series is represented by the Kootenai Formation, about 1,000 ft (300 m) thick of nonmarine conglomerate and purplish or greenish shale and mudstone, probably of Aptian age. It lies unconformably on other nonmarine deposits, probably equivalent to the Jurassic Morrison Formation and is succeeded by marine shales that are themselves of high Lower Cretaceous age at their base.

CALIFORNIA AND OREGON

The Lower Cretaceous rocks on the western side of the Sacramento Valley in northern California are part of the "Great Valley sequence" and form the Shasta Series, which has traditionally been divided into the Paskenta and Horsetown Formations, although other stratigraphic names are now used. It overlies the Upper Jurassic Knoxville Formation and is more than 17,000 ft (5,100 m) thick, ranging in age from Neocomian to Albian (Bailey and others, 1964, p. 130–133). At the north end of the valley, it oversteps the Knoxville and lies directly on the eroded surface of the deformed Jurassic and older rocks of the Klamath Mountains and their embedded plutons. The lowest beds are nearly identical with those of the Knoxville beneath and are distinguished mainly by a different species of *Buchia*. Higher up, they are somewhat more varied, with layers of graywacke, conglomerate, and mudstone, and thin limestone interbeds, the whole still a turbidite (flysch) deposit like the preceding Knoxville. To the west within the Coast Ranges are long narrow outliers of Lower Cretaceous rocks, which are in fault contact with the adjacent Franciscan assemblage and differ notably from it in their lack of metamorphic rocks, greenstone, and serpentinite even though sparse fossils in the Franciscan prove that part of it is younger. These outlying areas of Lower Cretaceous are evidently klippen of the Coast Range thrust sheet which forms the base of the main Great Valley sequence to the east.

Lower Cretaceous rocks are also exposed in the southern Coast Ranges and along the west side of the San Joaquin Valley, but their occurrence here is more sporadic than farther north.

In the structurally complex area of southwestern Oregon, small areas of Lower Cretaceous rocks are part of the Myrtle Group. The Myrtle lies unconformably on the Jurassic rocks of the Galice Formation and is faulted against the Dothan Formation (= Franciscan). Above its basal conglomerates are rhythmically bedded sandstones and mudstones with interbedded shelly layers, probably mainly shallow-water deposits with only a few deep-water turbidites.

WASHINGTON

In the northern part of Washington State, in the Methow River valley east of the Cascade Range, Cretaceous rocks occupy a downfaulted trough 20 mi (32 km) wide that extends southward from the Canadian border nearly to the Columbia River and for an even greater distance northward into British Columbia (Barksdale, 1975, p. 24–50). The rocks are thick and steeply folded but not metamorphosed like those that

flank them on the east and west. The rocks are all clastic and include lithic sandstone, arkose, black shale, and chert- and granite-pebble conglomerate, of marine origin (in the Buck Mountain, Goat Creek, Panther Creek, Harts Pass, and Virginian Ridge Formations), followed by continental arkose (Winthrop Sandstone), and topped by andesite tuff, breccia, and flows (Midnight Peak Formation). Total thickness is as much as 50,000 ft (15,000 m). The sequence is fossiliferous, and ranges in age from Neocomian to Cenomanian, with possible Jurassic at the base; the volcanics at the top (Kv) may be Turonian. All the rocks are represented as Lower Cretaceous (1K) on the Geologic Map.

UPPER CRETACEOUS

WESTERN GULF COASTAL PLAIN

The well-developed Upper Cretaceous sequence in Texas, the Gulf Series, provides a standard of reference for sequences elsewhere in the Coastal Plain. (For a useful summary, now somewhat outdated, see Adkins (1932, p. 400-516). Correlations are presented by Stephenson and others (1942).) On the Geologic Map, it is divided into the Woodbine Sand (uK₁) of Cenomanian age; the Eagle Ford Shale and Austin Chalk (uK₂) of Turonian, Coniacian, and Santonian age; the Taylor Marl (uK₃) of Campanian age; and the Navarro Group (uK₄) of Maestrichtian age. Most of the exposed Upper Cretaceous is normal neritic fossiliferous shales, marls, and chalks; however, marginal basal clastic rocks occur in the Woodbine, and terrestrial coal-bearing beds occur in the Navarro near the Rio Grande.

The Gulf Series is everywhere unconformable on the Comanche Series in surface outcrops. The Woodbine Sand truncates all the groups of the Comanche eastward into Arkansas. Southwestward, the Woodbine itself wedges out on the unconformity and disappears near Waco. Beyond, in west Texas, the Eagle Ford Shale (uK₂) lies with a hiatus on the Washita Group (1K₃). The Gulf Series is followed at all places by a disconformity, which separates it from the overlying Midway Group of Paleocene age.

The Woodbine Sand (uK₁) is mainly poorly consolidated sand, in part leaf bearing and probably non-marine, which intertongues with clays, some of them lignitic but some of them oyster-bearing nearshore brackish water deposits. In places it contains much volcanic material and in Arkansas includes interbeds of gravel.

The Eagle Ford Shale (uK₂) in its typical area is marine black shale but changes laterally into marls, and in much of west Texas it is calcareous flagstone

(Boquillas Flags). The Austin Chalk is a solid body of white chalk in its type area, but with a tongue of marl and clay (Bonham) in the middle toward the northeast. The typical chalk weathers to a rich black soil, extensively planted in cotton.

The Taylor Marl or Group (uK₃) is more varied than the units that precede it. In its typical area it is largely marl, but northeastward in Texas and Arkansas it contains many traceable units of sand and chalk that are separately named, and for some distance west of San Antonio the marls are partly or wholly replaced by the reef deposit of the Anacacho Limestone. The sand units are marginal deposits that indicate the ephemeral existence of nearby shorelines.

The Navarro Group (uK₄) is equally varied and has been divided into many named formations. North of Austin, for example, it consists of the Neylandville Marl, Nacatosh Sand, Corsicana Marl, and Kemp Clay. Near the Rio Grande, the lower half of the group passes into terrestrial coal-bearing deposits (Olmos Formation), which are more important in the Sabinas basin in Mexico to the south.

EASTERN GULF COASTAL PLAIN

Upper Cretaceous rocks reappear in the eastern part of the Gulf Coastal Plain, beyond the wide gap of the Mississippi Embayment where they are covered by Cenozoic deposits, and exhibit the same lithologies as in Texas, but arranged in a different order. (For a summary, now somewhat outdated, see Stephenson (1926, p. 231-245). Some of the later developments are presented by Eargle (1953).) Lower Cretaceous does not emerge in the region; the basal deposit is Upper Cretaceous throughout.

The sequence is best developed in Alabama, where it comprises the Tuscaloosa Formation (uK₁), approximately equivalent to the Woodbine Sand; the Eutaw Formation (uK₂), approximately equivalent to the Eagle Ford and Austin Formations; the Selma Chalk (uK₃), approximately equivalent to the Taylor Marl; and the Ripley Formation (uK₄), approximately equivalent to the Navarro Group.

The Tuscaloosa Formation consists of irregularly bedded nonmarine sands, clays, and gravels, in places lignitic and with fossil plants at many levels. The Eutaw Formation is a marine deposit, mainly glauconitic and micaceous sand with some interbedded clay. The Selma is a thin-bedded to massive chalk, much like the Austin although one stage younger (uK₃ rather than uK₂), but it fingers out into sands and clays northwestward in Mississippi and Tennessee and eastward in Georgia. The Ripley, like the Eutaw, is marine sands and clays, in part glauconitic. Toward the head of the Mississippi Embayment, in Kentucky

and Illinois, all the lower part of the Upper Cretaceous sequence wedges out by overlap, and so the Ripley lies directly on Paleozoic rocks.

Eastward in Georgia, South Carolina, and North Carolina, the Eutaw Formation wedges out, and so the higher units (uK₃ and uK₄) lie with a hiatus on the Tuscaloosa Formation (uK₁). In eastern Georgia and in South Carolina, the outcrop belt of the Upper Cretaceous rocks is much interrupted by overlapping Tertiary deposits, and the next large outcrop area is in southern North Carolina, where the Upper Cretaceous extends nearly to the coast along the broad upwarp of the Cape Fear arch. Here, the Tuscaloosa is a non-marine sandy and gravelly deposit as it is in Alabama, but the higher Black Creek and Pee Dee Formations (uK₃, uK₄) differ from the Alabama units, being marine clays, sands, and marls.

ATLANTIC COASTAL PLAIN

The Upper Cretaceous sequence is concealed by overlapping Tertiary deposits in northern North Carolina and throughout Virginia, but it reappears in Maryland and extends through New Jersey into the New York City area, resting on the Lower Cretaceous Potomac Group, which it bevels to the northeast (Spangler and Peterson, 1950, p. 15-52).

The Upper Cretaceous comprises the Raritan, Magothy, Matawan, and Monmouth Formations (or Groups), which span the whole period from Cenomanian to Maestrichtian, but they are all thin units and their outcrop bands are so narrow that the whole is represented on the Geologic map as an undivided unit (uK). The Upper Cretaceous is marine, in contrast to the Potomac Group, and is composed of sands, clays, and marls, including many beds of highly glauconitic greensand.

GREAT PLAINS AND ROCKY MOUNTAINS

By far the largest area of outcrop of Upper Cretaceous rocks in the United States is in the central and northern Great Plains and the contiguous Rocky Mountains (fig. 15). These rocks are the product of a single great seaway that connected the Gulf of Mexico on the south and the Arctic Ocean on the north. The eastern feathered edge of the deposit is in eastern Kansas and western Iowa and Minnesota, whence it extends 800 mi (1,300 km) westward through the Rocky Mountains to the front of the Cordilleran thrust belt in the Northern Rocky Mountains and the eastern Great Basin. Throughout this area the Upper Cretaceous was originally a continuous deposit; it is now interrupted in the Rocky Mountains where it has been eroded from the uplifts, and it is covered in many areas in the Great Plains by Tertiary deposits.

There is a vast literature on the Upper Cretaceous in the region which it would be fruitless to attempt to document—on its stratigraphy, paleontology, sedimentology, and economic potential—but most of the publications deal with special areas or problems. General syntheses are few; Cobban and Reeside (1962) have presented the correlations, and a general survey of the rocks and their problems appears in the "Geologic Atlas of the Rocky Mountain Region" (McGookey and others, in Mallory, 1972, p. 190-228).

The gross units of the Upper Cretaceous in the region are the Dakota Group (uK₁), the Colorado Group (uK₂), the Montana Group (uK₃), and the Laramie and associated formations (uK₄). These are approximately equivalent to the Woodbine Sand, the Eagle Ford Shale and Austin Chalk, the Taylor Marl, and Navarro Group, respectively, of the western Gulf Coastal Plain, and the symbols are used interchangeably between the two regions, although they are not precisely correlative in detail. Thus, the Dakota Group (uK₁) toward the east is basal Upper Cretaceous, but as mapped farther west it includes Lower Cretaceous and in places is entirely Lower Cretaceous; the upper part of the Montana Group (uK₃) includes equivalents of the lower part of the Navarro Group.

The Upper Cretaceous sequence is 2,000 ft (600 m) thick or less in the eastern Great Plains, but it thickens to 20,000 ft (6,000 m) at the front of the Cordilleran thrust belt on the west. As these thicknesses imply, the dominant sediment source was in the Cordilleran region to the west, where orogenic deformation was in progress during much of the period and was accompanied by thrusting, volcanism, and batholithic intrusion, whose erosion products were shed eastward into the Cretaceous seaway. The eastern side of the seaway provided only minor sediment sources; only the basal Dakota Sandstone along the eastern margin appears to have been derived from the craton.

The Upper Cretaceous sequence in the Great Plains is relatively simple. The Dakota Sandstone (uK₁) at the base is a terrestrial marginal deposit. The succeeding Colorado Group (uK₂) includes dark shale and widespread carbonate deposits—the thin Greenhorn Limestone in the Benton Group below, and the thicker Niobrara Chalk above, which is much like the Austin Chalk of the western Gulf Coastal Plain and of about the same age. The dark marine Pierre Shale dominates the Montana Group (uK₃) above, but it is topped by thinner marginal deposits of the Fox Hills Sandstone. This is succeeded by terrestrial coal-bearing deposits known from place to place as the Laramie, Lance, or Hell Creek Formations (uK₄), which are overlain, mostly conformably, by the similar Paleocene terrestrial deposits of the Fort Union Formation.

Along the eastern margin of the Upper Cretaceous outcrop its subdivisions are thin and heavily drift covered; so, they are not divided on the Geologic Maps of Iowa or Minnesota, nor on the Geologic Map of the United States. In considerable areas in northern Minnesota, the thin unconsolidated Coleraine Formation of Upper Cretaceous age lies between the glacial drift and the Precambrian basement (Sloan, 1964) but is not shown on the Geologic Map (King and Beikman, 1974, fig. 13).

Complications develop westward in the Rocky Mountain Region. Carbonate deposits, such as the Niobrara, fade out in the marine shales, and in the shales appear westward-thickening wedges of coarser clastics—shallow-water sandstones at their proximal ends changing distally into coal-bearing terrestrial deposits. A minor wedge, the Frontier Formation, occurs low in the Colorado Group in western Wyoming, but the main wedges, which are higher up, near the middle of the Montana Group, are known in the Southern Rocky Mountains and Colorado Plateau as the Mesaverde Formation and in Montana as the Judith River Formation. The Mesaverde wedge partitions the marine shales into the Mancos Shale below and Lewis Shale above. The Mesaverde wedges have irregular distal ends, and so a unit referred to as Mesaverde at one place may be higher or lower stratigraphically than the Mesaverde at another and the ages of the enclosing marine shales may also differ accordingly.

These intertonguing relations pose problems for representation on the Geologic Map. It would be instructive to be able to differentiate on the map between the marine deposits and the clastic wedges with their terrestrial deposits, but the various wedges produce so complex a pattern that it is not feasible on the scale of the map. On the Geologic Map the divisions shown—the Dakota, Colorado, Montana, and Laramie—are therefore solely time-stratigraphic, regardless of facies at any particular place. The Montana Group covers an enormous area in the northern Great Plains, occupying nearly half of North and South Dakota, and its vast Pierre Shale has no regionally distinguishable subdivisions. In the plains of Montana, however, clastic wedges such as the Judith River Formation make subdivision possible. Here, in order to clarify the geology and bring out the structure, the Montana Group is divided into two parts, uK_{3a} and uK_{3b} , using the base of the Judith River Formation as the line of separation.

In northeastern Utah, along the south edge of the Uinta basin, the Castlegate Sandstone in the clastic wedge of the Mesaverde Group is traceable westward into the coarser Price River Formation. The Price River becomes a red bouldery piedmont deposit on the edge of the Wasatch Mountains, where it lies uncon-

formably on a rough erosion surface of strongly deformed older Mesozoic and Paleozoic rocks (Spieker, 1946, p. 130–132). Moreover, beneath the unconformity is an older coarse piedmont deposit, the Indianola Formation, of Colorado age. There is no unconformity at the base of the Indianola, but it is obviously related to a newly deformed terrane not far to the west. The Mesaverde clastic wedge in this segment can be directly related to orogenic activity in the Cordilleran belt to the west, and relations are probably similar for most of the Upper Cretaceous clastic wedges of the Rocky Mountain Region, although the actual connections are not so clearly preserved as in Utah. The different pulses of orogenic activity produced a succession of transgressions and regressions in the Upper Cretaceous deposits, of which there are four principal ones; transgressions are produced when the marine shales spread westward, and regressions when the clastic wedges advanced eastward (McGookey and others, in Mallory, 1972, p. 206).

The piedmont deposits in Utah of Colorado and Montana age are manifestations of the Sevier orogeny (Armstrong, 1968, p. 444–449), in the Cordilleran miogeosyncline in Utah, southeastern Idaho, and southwestern Wyoming, that resulted in eastward transport of thick miogeosynclinal Paleozoic rocks over thinner cratonic sequences on a series of gently dipping thrust faults. These episodes of thrusting began during the Jurassic and culminated during Late Cretaceous time, although there were minor episodes as late as the Eocene Epoch (Armstrong and Oriel, 1965, p. 1857–1861).

Different in style and time from the Sevier orogeny is the type Laramide orogeny in the eastern ranges of the Central and Southern Rocky Mountains, generally assumed to have terminated the Cretaceous Period in those areas. The Laramide orogeny resulted mainly in upthrusting of the ranges and depression of the intervening basins. These movements began in Late Cretaceous time, as indicated by thickness variations in the higher Cretaceous basin deposits in the Central and Southern Rocky Mountains, but the principal unconformities resulting from the orogeny are between the Paleocene and Eocene deposits, rather than at the top of the Cretaceous sequence. In the Northern Rocky Mountains, however, from Montana northward into Alberta, thrusting like that produced during the Sevier orogeny continued later and reached its climax during Laramide time (latest Cretaceous and Paleocene).

The true top boundary of the Cretaceous System in the Rocky Mountains was long controversial—the “Laramie question” which was debated for many years following the work of the Hayden Survey a century ago

(Merrill, 1904, p. 647-658). It was observed that *Triceratops*, the last of the dinosaurs, was found in the Laramie beds, whereas Tertiary mammals were abundant in the succeeding Fort Union Formation; nevertheless, it was claimed that the fossil plants in both the Laramie and Fort Union were of Tertiary aspect. During Laramie and Fort Union time, the Rocky Mountains were rising, as shown by erosional debris in these formations, and it was assumed that an immense unconformity lay concealed in these deposits in the plains, which would presumably mark the top of the Cretaceous. Much futile effort was expended in a search for this unconformity. These questions are now largely resolved, and the vertebrate and paleobotanical evidence reconciled. Concepts have been further clarified by recognition of the Paleocene as a separate series of the Tertiary Period and by classification of the Fort Union as Paleocene rather than Eocene.

PACIFIC COASTAL AREA

Upper Cretaceous rocks of the Pacific coastal area occur mainly in California, and in a few minor extensions in southwestern Oregon. In northern California they are the upper part of the "Great Valley sequence," and have sometimes been called the Chico Series. This term is inappropriate, as the type Chico is a thin near-shore deposit of Campanian age that overlaps the basement rocks of the Sierra Nevada, whereas the main body on the west side of the valley is a more complete sequence of deeper water deposits more than 15,000 ft (4,500 m) thick, divisible into a number of formations (Bailey and others, 1964, p. 133-135). In one segment it consists of the Venado, Yolo, Sikes, Funks, Guinda, and Forbes Formations, which are of Cenomanian to Campanian age. All of them are interbedded sandstone, siltstone, and shale—a typical turbidite or flysch sequence—the different formations being distinguished mainly by varying proportions of the coarse and fine clastic components. In places the lower part contains lenses of slumped material, including large boulders of quartz diorite, evidently derived from Sierra Nevada basement, against which the deposit probably overlaps in subsurface not far to the east.

Upper Cretaceous rocks extend southward along the west side of the San Joaquin Valley and are well displayed along the eastern flank of the Diablo Range, where they are 25,000 to 30,000 ft (7,600-9,000 m) thick, with the thick Panoche Formation below and the thin Moreno Shale above. The Panoche is again an alternation of sandy and shaly beds, a turbidite or flysch sequence, but it locally contains thick lenses of conglomerate that includes clasts of porphyry and granitic rocks. The Panoche lies in places on thin rem-

nants of Lower Cretaceous and Jurassic rocks, but its base is mainly faulted against the Franciscan rocks of the Diablo Range along a segment of the Coast Range thrust. The Upper Cretaceous sediments were derived mainly from the Sierra Nevada to the east, and there is no detritus that can be attributed to the crystalline basement of the Salinian block, across the San Andreas fault immediately to the west. Within the Salinian block itself, late Upper Cretaceous rocks (Campanian and Maestrichtian) of the Asuncion Group, of a different facies, lie on the crystalline rocks.

Other thick sequences of Upper Cretaceous rocks are preserved in places farther south in the Coast Ranges and in the western part of the Transverse Ranges, and Upper Cretaceous deposits lie unconformably on the Jurassic sequence (Bedford Canyon and Santiago Peak Formations) in the Santa Ana Mountains, at the northwestern end of the Peninsular Range of southern California. These last range in age from Cenomanian to Campanian and are divided into the Trabuco, Ladd, and Williams Formations.

At the eastern edge of the Klamath Mountains near the California-Oregon border, deformed and metamorphosed Mesozoic and Paleozoic eugeosynclinal rocks are overlain by the Upper Cretaceous Hornbrook Formation, which dips gently eastward beneath the Eocene volcanic rocks of the Cascade Range. It is a body of sandstone, siltstone, and mudstone about 2,500 ft (760 m) thick, with marine fossils of Cenomanian and Campanian age at several levels (Peck and others, 1956).

CONTINENTAL DEPOSITS (Kc)

Continental deposits of Cretaceous age (Kc) are separately mapped in parts of the Cordilleran Region. The designation is used especially for the coarser poorly stratified deposits. Excluded are the finer grained stratified deposits more intimately associated with the normal marine sequence, such as the Lower Cretaceous Gannett Group and Wayan and Kootenai Formations, and the Upper Cretaceous coal-bearing terrestrial wedges of the Mesaverde and other formations. It is used especially in central Utah for the coarse piedmont deposits next to the Sevier orogenic belt, such as the Indianola and Price River Formations.

Farther west, in the Great Basin, are small isolated areas of Cretaceous continental deposits that probably formed in local basins. They are typified by the Newark Canyon Formation of the Eureka district, central Nevada (Nolan and others, 1956, p. 66-70), which is a heterogeneous deposit about 2,000 ft (600 m) thick of siltstone and conglomerate, with many layers of freshwater limestone, that lies on the truncated and eroded surface of all the Paleozoic formations of the

district. The limestone contains gastropods of Early Cretaceous age, as well as plant and fish fossils.

About 150 mi (250 km) farther northwest, in the Jackson Mountains of northwestern Nevada, are other small areas of Cretaceous continental deposits (Willden, 1958), which lie on Triassic and Permian eugeosynclinal rocks (FPe). The King Lear Formation consists of conglomerate and siltstone with some beds of freshwater limestone that contain Lower Cretaceous gastropods like those in the Newark Canyon Formation. It is overlain in places by another conglomeratic deposit, the unfossiliferous Pansy Lee Formation, which likewise predates the Tertiary volcanic rocks of the area. Both units are indicated as Cretaceous continental deposits (Kc) on the Geologic Map.

In southern Nevada, east of Las Vegas, is another set of Cretaceous continental deposits, which lie unconformably on deformed older rocks and are themselves much deformed (Longwell and others, 1965, p. 41-45). On the eastern flank of the Muddy Mountains are the Willow Tank Formation and Baseline Sandstone, about 4,000 ft (1,200 m) thick, which contain fossil plants of middle Cretaceous age. The Willow Tank and Baseline are succeeded by the mass of the much coarser Overton Funglomerate, which contains large blocks and slabs of the Paleozoic formations. Farther west, southeast of Frenchman Mountain, is the Thumb Formation, much like the Willow Tank and Baseline Formations, but containing lenses of coarse breccia composed of Precambrian metamorphic rocks. All these units are synorogenic deposits, laid down while deformation was in progress in the region.

In the ranges of the southwestern desert region of Arizona, many areas of Mesozoic sedimentary rocks are indicated on the State Map (1969). They are a deformed sequence of shale, sandstone, limestone, and conglomerate, less metamorphosed than the rocks on which they lie and overlain unconformably by Tertiary volcanic rocks. Although unfossiliferous, they are classed as Cretaceous continental deposits (Kc) on the Geologic Map.

Far to the north, in the Purcell Trench north of Pend Oreille Lake in northern Idaho, are small areas of the Sandpoint Conglomerate, formed of clasts of the Belt rocks, lying in a terrane of the Belt Supergroup and Cretaceous plutons (Harrison and others, 1972, p. 6). No data for its age are available; it was once assigned to the Paleozoic, but the preponderance of evidence now suggests that it is Cretaceous (Kc) and is so indicated on the Geologic Map.

EUGEOSYNCLINAL DEPOSITS (Ke)

Cretaceous eugeosynclinal deposits are dealt with at the close of a later section entitled "Upper Mesozoic."

VOLCANIC ROCKS (Kv)

Small areas of volcanic rocks of Cretaceous age (Kv) are shown in various parts of the Cordilleran Region on the Geologic Map.

Of these, the most significant are those surrounding the Boulder batholith in west-central Montana (Robinson and others, 1968, p. 563-569). The Elkhorn Mountain Volcanics which adjoin the batholith and form part of its roof are remnants of a volcanic accumulation that was probably originally 10,000 ft (3,000 m) thick, the lower part mainly andesite and rhyodacite breccia and lava, the middle part rhyolite welded tuff, and the upper part erosional debris derived from the lower members. It lies unconformably on Upper Cretaceous sedimentary rocks of Santonian age and is overlain unconformably by middle Eocene volcanic rocks. Radiometric dating has yielded ages of about 73 to 78 m.y. and suggests that the eruptive episode lasted for about 4 m.y. in Campanian time. The period of eruption overlapped that of emplacement of the Boulder batholith itself, which has been dated between 71 and 82 m.y.

Northeast of the Elkhorn Mountain Volcanics and the Boulder batholith, in the outer thrust zone of the Northern Rocky Mountains, are the Adel Mountain Volcanics, which are somewhat younger, more alkalic, and petrographically different.

Farther southeast in Montana, between the Crazy Mountains and Bearpaw Mountains, the volcanic rocks of the Grey Cliff field lie on various Upper Cretaceous units as young as the Hell Creek Formation (uK₄) but are indicated on the source maps as Cretaceous. The Late Cretaceous and Paleocene rocks of the Crazy Mountains basin themselves contain large quantities of andesitic debris but are included in the stratified sequence on the Geologic Map.

Other areas of Cretaceous volcanic rocks (Kv) are shown on the Geologic Map in southwestern New Mexico and southeastern Arizona. Some of them are interbedded with fossiliferous sedimentary rocks as old as Lower Cretaceous, and others follow conformably on the highest Cretaceous sediments. The Geologic Map of Arizona (1969) likewise indicates as Cretaceous the older volcanic rocks of many of the ranges in the southwestern part of the State. Evidence for their age, however, is inconclusive, and the Cretaceous designation is based mainly on structural evidence; they are cut by intrusives of supposed "Laramide" age and are unconformably overlain by undoubted Tertiary volcanic rocks. Some of these rocks may indeed be Cretaceous, but an early Tertiary age for most of them seems to accord better with the volcanic sequence in adjoining States; they are therefore marked as lower Tertiary volcanics (ITv) on the Geologic Map.

UPPER MESOZOIC

UPPER MESOZOIC EUGEOSYNCLINAL DEPOSITS (uM₂e)

The upper Mesozoic eugeosynclinal deposits are primarily represented by the Franciscan Formation, or assemblage, which dominates the coastal region of California, with extensions northward into southwestern Oregon and southward into Baja California (Bailey and others, 1964). The Franciscan forms much of the surface of the Coast Ranges north of San Francisco Bay and extends into Oregon as the Dothan Formation. Similar rocks extend westward to the coast, but part of them in this segment are treated separately as "Cretaceous eugeosynclinal deposits" (Ke). South of San Francisco Bay the Franciscan forms the basement northeast of the San Andreas fault as far as the south end of the San Joaquin Valley. Southwest of the San Andreas fault in this latitude is the different basement terrane of the structural block of Salinia, composed of the metamorphic Sur Series (u₂) and intrusive Cretaceous granite (Kg), but the Franciscan reappears along the coast in the southern Coast Ranges, beyond the Nacimiento fault. South of the Transverse Ranges in southern California is a large area of Franciscan rocks, mainly offshore, whose presence is indicated by small outcrops on Santa Catalina Island and in the Palos Verdes Hills and by abundant blueschist and other Franciscan debris in the San Onofre Breccia of Miocene age along the coast.

The Franciscan is a chaotic partly metamorphosed assemblage of graywacke and shale, with interbedded pillow basalt, radiolarian chert, and minor limestone, in which masses of serpentinite and other ultramafic rocks are embedded; its thickness is indeterminate but is on the order of 30,000 ft (9,000 m) or more. Fossils are rare, but enough have now been discovered to indicate that it includes rocks of Late Jurassic (Tithonian) to Late Cretaceous (Turonian and even Campanian) age, approximately coeval to the "Great Valley sequence" to the east and younger than the mid-Jurassic Nevadan orogeny. No base of the Franciscan is known, but it probably lies on an oceanic crust. The assemblage is a submarine trench and ocean-floor deposit that has been crowded and subducted against the continent to the east and added to it during late Mesozoic and early Tertiary time. The next strata in depositional contact above the Franciscan are Tertiary and commonly Miocene; older Tertiary and Cretaceous rocks which adjoin it are commonly faulted against it.

Parts of the Franciscan are a melange of tectonically disordered blocks and slabs of all sizes, formed of rocks of heterogeneous lithologies, origins, and ages (Hsu, 1968). Other parts are straight-forward sequences, or "broken formations" at most. In those parts of the

northern Coast Ranges where the structure has been studied in most detail, thick units of melange alternate with thick units of more straightforward sequences. In these areas, the Franciscan is found to be divided into a succession of east-dipping tectonic slices, the higher slices to the east containing the oldest rocks of Jurassic age and the lower slices to the west containing rocks of successively younger Cretaceous ages. Further complications and disorder are produced by north-northwest-trending strike-slip faults of the San Andreas fault family, which further sheared and displaced the rocks during Tertiary time.

Strike-slip faulting of large displacement is probably responsible for the introduction of the crystalline basement mass of Salinia between the two Franciscan areas in the southern Coast Ranges. It is a reasonable assumption that all the now-separated bodies of Franciscan rocks originally formed a continuous body in a deep-water offshore regime and that Salinia is a sliver of continental rocks, detached from some area farther south and moved into a position foreign to it. The granites of Salinia are shown by radiometric dating to be of Cretaceous age, as young as or younger than the Franciscan rocks that adjoin them; yet, their only contacts are faults, and there is no indication of any contact metamorphism in the Franciscan or any debris in the Franciscan derived from Salinia.

The potassium feldspar content of the graywackes in the Franciscan and the Great Valley sequence is of interest (Bailey and others, 1964, p. 139-147). The graywackes in the Great Valley sequence show a progressive increase in potassium feldspar from Jurassic to Upper Cretaceous time, suggesting that during this interval the granitic plutons of the Sierra Nevada and Klamath Mountains were becoming more and more unroofed and subject to erosion. Remarkably, graywackes in the coeval Franciscan immediately to the west contain little or no potassium feldspar, except in the coastal belt (Cretaceous eugeosynclinal deposits, Ke). Possibly the source of the Franciscan graywackes was different from that of the Great Valley sequence.

The Franciscan rocks have been rather pervasively metamorphosed to the blueschist (high-pressure low-temperature) facies (Bailey and others, 1964, p. 89-112). For the most part, this is barely perceptible; a zeolite facies with laumontite is near the coast, and farther inland the graywackes have been jadeitized, without altering their primary sedimentary structures. Higher grade blueschist with pumpellyite, glaucophane, and lawsonite occurs in a band along the eastern side of the Franciscan area, close to the Coast Range thrust, and its extreme phase has been named the South Fork Mountain Schist (Blake and others, 1967); it is marked by a metamorphic overprint on the

Geologic Map. A large outlying area, the Colebrooke Schist, occurs in southwestern Oregon (Coleman, 1972, p. 27-58). The schists decrease in grade and intensity downward from the sole of the fault, and so rocks on the ridgetops are more metamorphosed than those in the intervening valleys. Radiometric dating by the K/Ar method indicates that the metamorphism of the Franciscan rocks has a range in age from 70 to 150 m.y., or about the same time span as the age of the assemblage itself as indicated by fossils, showing that metamorphism went on hand in hand with the sedimentation (Suppe and Armstrong, 1972). The oldest dates are in the South Fork Mountain Schist on the east, and younger dates are farther west.

Also shown on the Geologic Map as upper Mesozoic eugeosynclinal deposits (with a metamorphic overprint) are an assortment of metamorphic rocks of greenschist facies east of the Franciscan area in southern California. They include the Pelona Schist, close to the San Andreas fault in the San Gabriel and San Bernardino Mountains, the Orocopia Schist in the desert ranges east of the Salton Trough farther southeast, and the Rand Schist in the Mojave Desert to the northeast (Ehlig, 1968). Although these have been called Precambrian, they are everywhere in fault contact with the true Precambrian as well as with the late Paleozoic Mount Lowe Granodiorite, and they lack the pervasive plutonism of the Precambrian rocks. Various lines of indirect evidence suggest that the schists are 70 to 100 m.y. old. The original rocks were interbedded graywackes, siltstones, and shales; they may be more or less equivalent to the Franciscan rocks to the west, but in a greenschist rather than a blueschist facies.

In the northern part of Washington State, on the western flank of the Cascade Range, is the Nooksack Group, which contains fossils of Late Jurassic and Early Cretaceous age (Kimmeridgian to Valanginian) (Misch, 1966, p. 118) and is therefore shown as upper Mesozoic eugeosynclinal deposits (uMke) on the Geologic Map. The Nooksack is a flyschlike sequence of graywackes and siltstones containing volcanic detritus and a few lenses of conglomerate, the whole a deep-water deposit laid down under conditions of tectonic unrest. As described, the Nooksack somewhat resembles the Franciscan but does not have its chaotic structure.

CRETACEOUS EUGEOSYNCLINAL DEPOSITS (Ke)

In the northern Coast Ranges, a western belt of Franciscan-type rocks differs significantly from the main body of the Franciscan farther east; the belt extends for 150 mi (250 km) along the coast south of Cape Mendocino and for as much as 30 mi (50 km) inland. Its rocks have less structural disorder than those farther

east and are mainly graywackes; interbedded lava and chert are rare. The graywackes contain appreciable quantities of potassium feldspar, in contrast to the Franciscan farther east (Bailey and others, 1964, p. 140); graywackes containing potassium feldspar in the San Francisco Peninsula might be correlative. The rocks of the coastal belt are the youngest part of the Franciscan assemblage; at least part of the belt is of Late Cretaceous age, as indicated by occasional fossils, and it is accordingly mapped as Ke. However, dinoflagellates and angiosperm pollen from many localities in the belt are definitely Eocene (Evitt and Pierce, 1975), thus greatly extending the time during which rocks of the Franciscan assemblage accumulated.

MESOZOIC PLUTONIC AND INTRUSIVE ROCKS

Plutonic and intrusive rocks of Mesozoic age are a significant component of the western part of the Cordilleran Region, where they form about 10 percent of the surface (fig. 16). They are less abundant in the eastern part of the Cordillera (where the intrusives are mainly Tertiary) and are minor in the eastern United States, except for the granitic White Mountain Series in northern New England. All the Mesozoic periods are represented, although plutonic rocks of Cretaceous age are by far the most abundant. The ages of the plutonic and intrusive rocks are indicated by their relations to enclosing rocks and more often by radiometric dating. Radiometric dates are now available for most of the important plutonic bodies in the United States, and such ages can be extrapolated further to undated adjacent bodies of similar character.

TRIASSIC GRANITIC ROCKS (Tg)

Granitic rocks of Triassic age occur in a few places in the western part of the Cordilleran Region (fig. 17).

One group of quartz monzonite and granodiorite plutons runs along the eastern edge of the Sierra Nevada in eastern California, from Bishop northwestward past Mono Lake, and into some of the ranges of western Nevada. The intrusive episode represented, designated as the Lee Vining epoch (Evernden and Kistler, 1970, p. 19), has been dated by K/Ar methods at between 195 and 210 m.y., or Middle to Late Triassic. These rocks are intruded by the more prevalent Jurassic and Cretaceous plutonic rocks of the same area.

In the eastern part of the Blue Mountains of north-eastern Oregon, near Sparta, a group of much-sheared albitized granites are distinctly older than the quartz diorite and granodiorite plutons of Cretaceous age (Gilluly, 1933, p. 66-67). Relations to adjacent supracrustal rocks and intrusives suggest that they are of Triassic age, which has been confirmed by a few

radiometric dates in the range of 210 to 250 m.y. (G. W. Walker, oral commun., 1971).

Several bodies of Triassic granitic rocks occur in the crystalline complex of northern Washington. In the core of the Cascade Range is the Marblemount Quartz Diorite, which predates the Cretaceous metamorphism of the range and is overlain unconformably by the Cascade River Schist (ms) (Misch, 1966, p. 105). Dating of zircons by U/Pb methods yields ages of 215 to 220 m.y., or Early Triassic (Mattinson, 1970), and later metamorphism has not reset the zircon ages. In the Okanogan Range to the east are the granitic rocks of the Toats Coulee Magma Series (Hibbard, 1971, p. 3029–3031), which is composed of granodiorite, tonalite, and tonalite porphyry and which is premetamorphic or synmetamorphic to a Late Triassic orogeny and older than the adjacent plutons of the Cretaceous Horseshoe Basin Magma Series. The rocks have yielded a K/Ar age of 194 m.y., or Late Triassic.

TRIASSIC MAFIC INTRUSIVES (Fi)

Mention has already been made of the diabase intrusives in the Newark Group of the Appalachian Region from New England to Virginia. The thick Palisades sill of eastern New Jersey has been dated radiometrically at 190 to 200 m.y. (Erikson and Kulp, 1961).

JURASSIC GRANITIC ROCKS (Jg)

Jurassic granitic rocks are more extensive than those of the Triassic in the western part of the Cordilleran Region (fig. 18). They also occur in northern New England (fig. 16). They are, however, by no means as extensive as implied on the Geologic Map of the United States of 1932, where all the Mesozoic plutonic rocks of the Cordilleran Region were assigned to the Jurassic; a large part of these is now known to be of Cretaceous age. Jurassic granitic rocks are absent, for example, in all the plutons of the northern part of the Cordillera in the United States, in Montana, Idaho, Washington, and northeastern Oregon.

In California, Jurassic granitic rocks occur in the Sierra Nevada and the Klamath Mountains. In the Sierra Nevada, the Jurassic granitic rocks occur east and west of the axis of the range, which is formed of Cretaceous rocks of the main Sierra Nevada batholith (Bateman and Wahrhaftig, 1966, p. 115–122). Field relations indicate more than one Jurassic intrusive epoch; some plutons in the western foothills are truncated by the Melones fault zone, whereas others are not. This is confirmed by K/Ar dating, which indicates an early episode of intrusion with ages of 160 to 180 m.y., called the Inyo Mountains intrusive epoch and represented chiefly east of the Sierra Nevada, and a

later episode with ages of 132 to 148 m.y., called the Yosemite intrusive epoch and represented on the western slope of the Sierra Nevada (Evernden and Kistler, 1970, p. 17–19). (These are not separated on the Geologic Map.) The Jurassic granitic rocks of the western flank are dominantly quartz diorites and granodiorites, less silicic than the Cretaceous granitic rocks of the main batholith. In the foothills the Jurassic granitic rocks form large equidimensional plutons embedded in the Jurassic eugeosynclinal rocks, but they merge to the east into a more continuous body which forms the western part of the main batholith, as at the lower end of Yosemite Valley (El Capitan Granite, and so forth). Except for a few minor Cretaceous plutons, all the granitic rocks of the Inyo and White Mountains are Jurassic of the first epoch.

The granitic rocks of the Klamath Mountains of northern California and southwestern Oregon are all Jurassic and form large diorite and granodiorite plutons elongated parallel with the trends of the country rocks; they are most abundant in the Central Metamorphic belt and the Western Paleozoic and Triassic belt (Hotz, 1971, p. 15–17). Three epochs of intrusion are recognized by radiometric dating: from 165 to 167 m.y., from 145 to 155 m.y., and from 127 to 140 m.y., the first and last broadly equivalent to the two intrusive epochs in the Sierra Nevada. (Again, these are not differentiated on the Geologic Map.) The Shasta Bally pluton at the south end of the mountains, of the last intrusive epoch, is overlain unconformably by the earliest Lower Cretaceous rocks of the Great Valley sequence.

Eastward in the Great Basin of Nevada, Jurassic granitic rocks (as dated radiometrically) seemingly have a random distribution with respect to the Cretaceous granitic rocks. All the plutons, as exposed at the surface, are smaller than those in the Sierra Nevada, but the true dimensions of some are obscured by Tertiary cover. The easternmost Jurassic pluton is the Panther Spring Granite, intrusive into the Cambrian strata of the House Range in western Utah and dated at 143 m.y.

In northern New England, far from the areas just discussed, is the White Mountain Plutonic Series, named for its prominent development in central New Hampshire but with outlying plutons in Vermont on the west and Maine on the east (Billings, 1956, p. 129–135, 145–146). It is a set of fresh crosscutting intrusions younger than the orogenies in the Paleozoic rocks and principally forms ring dikes and cauldron subsidences, but with one large batholith (actually an aggregate of coalesced ring dikes). It consists of alkalic rocks, with some mafic end members, but mainly of quartz syenite and alkali granite, of which the most

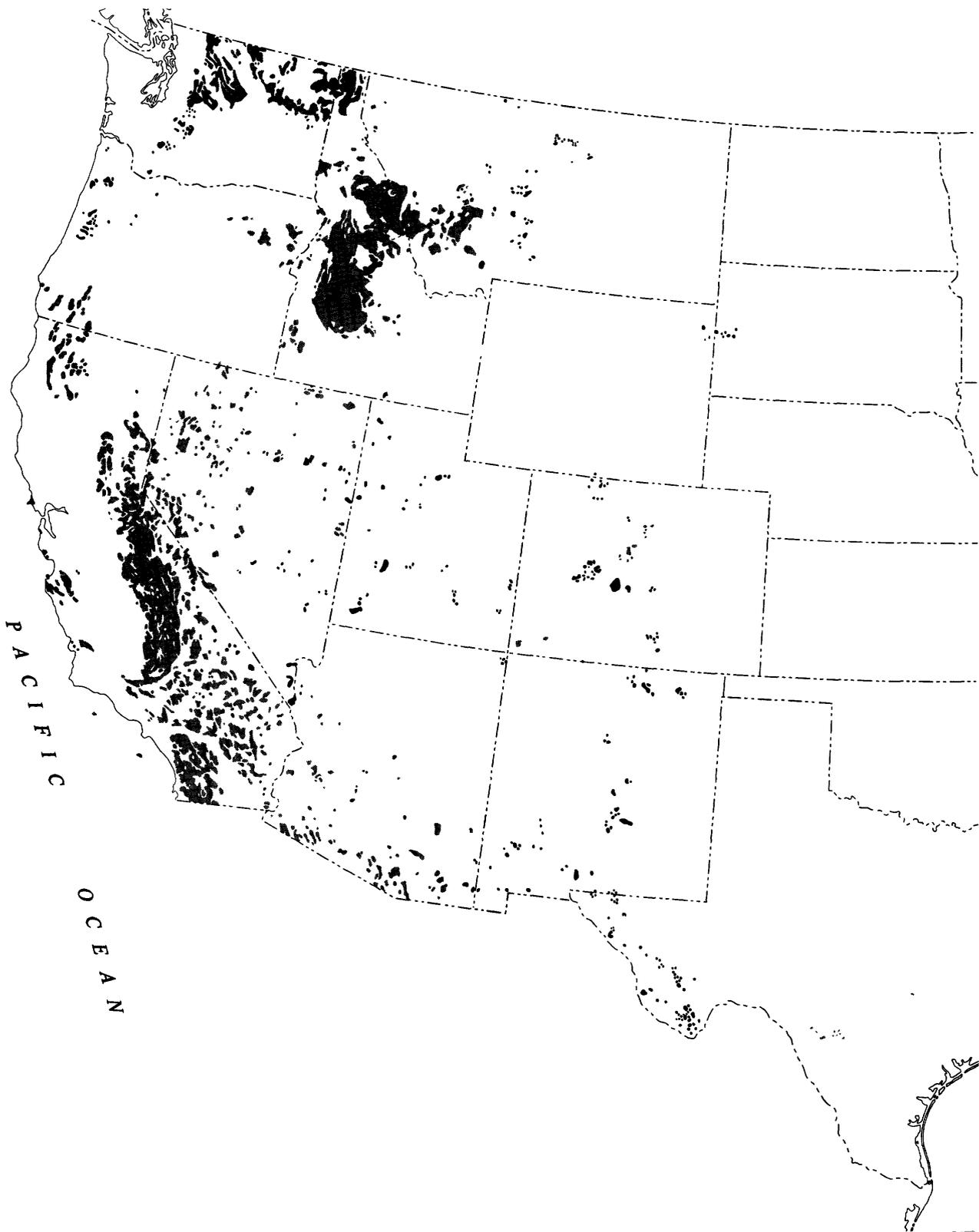


FIGURE 16.—The United States, showing in separate patterns areas mapped as Mesozoic and Cenozoic plutonic and intrusive rocks on Geologic Map of the United States. Mesozoic rocks include units of Triassic plutonic and intrusive rocks (Tg, Ti), Jurassic plutonic rocks (Jg, Jmi), and Cretaceous plutonic and intrusive rocks (Kg, Kg1, Kg2, Kg3, Kgn, Ki). Cenozoic rocks include units of Tertiary intrusive rocks (Ti).

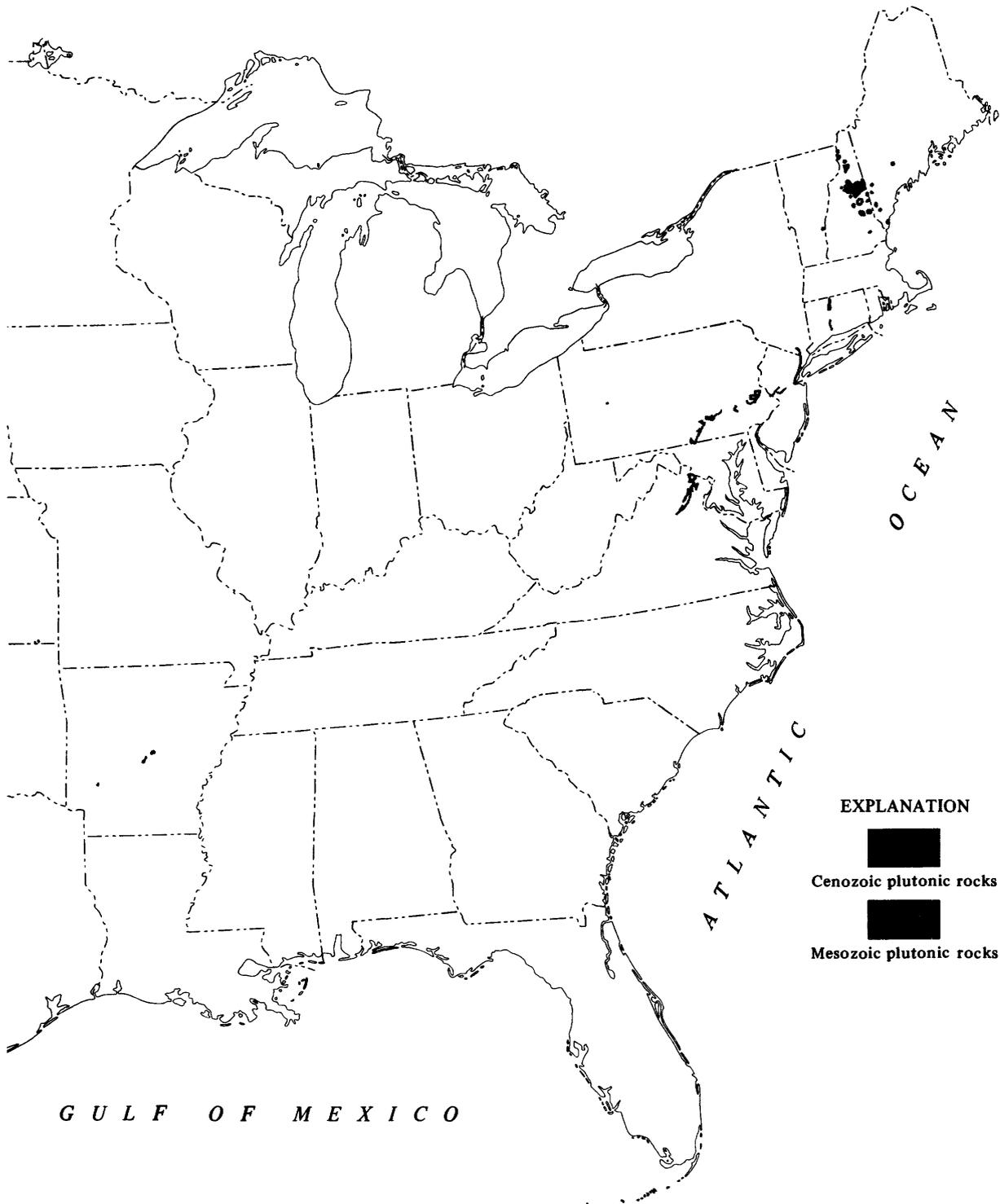


FIGURE 16.—Continued.

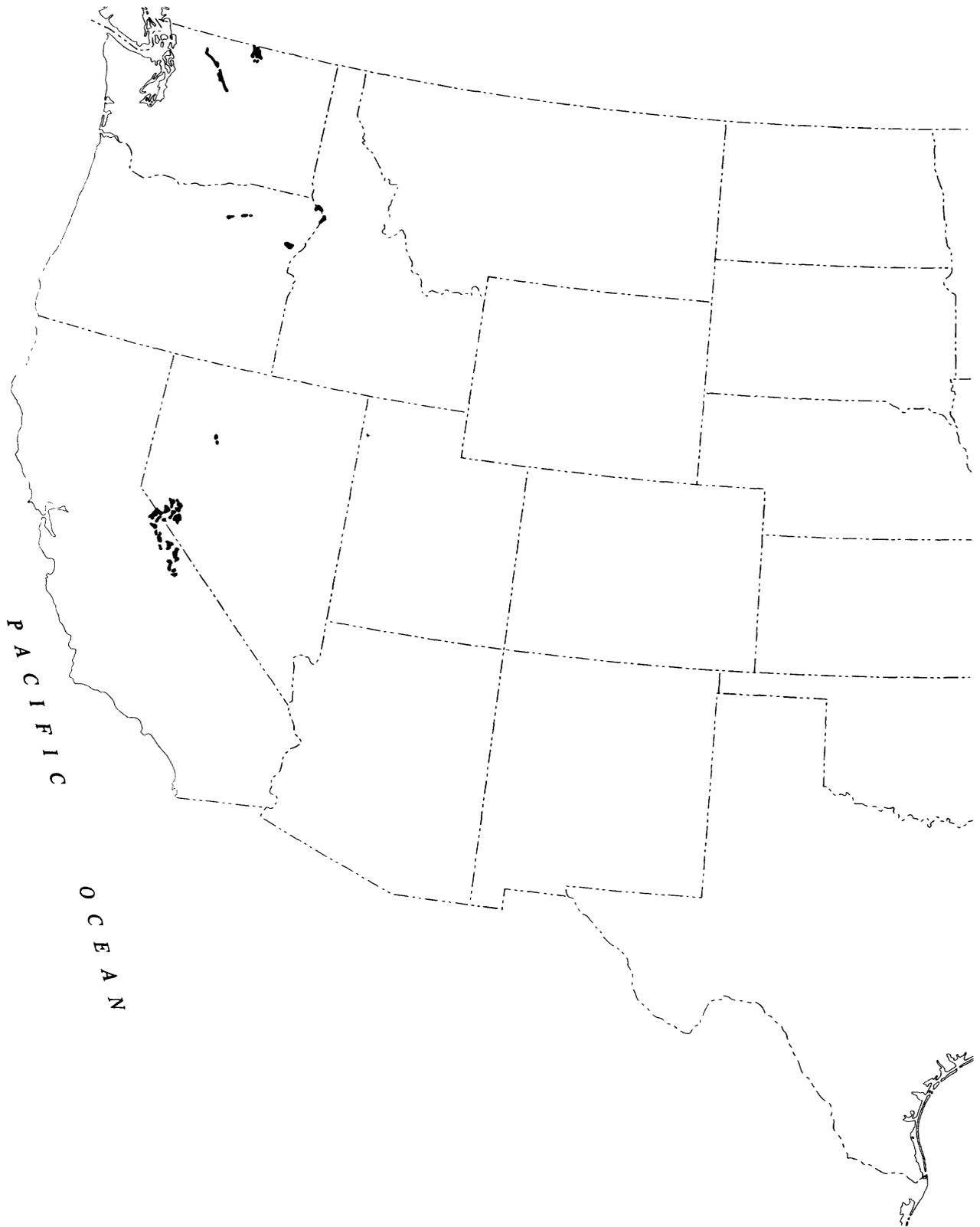


FIGURE 17.—Western United States, showing areas of Triassic granitic rocks (Fig) as mapped on Geologic Map of the United States.

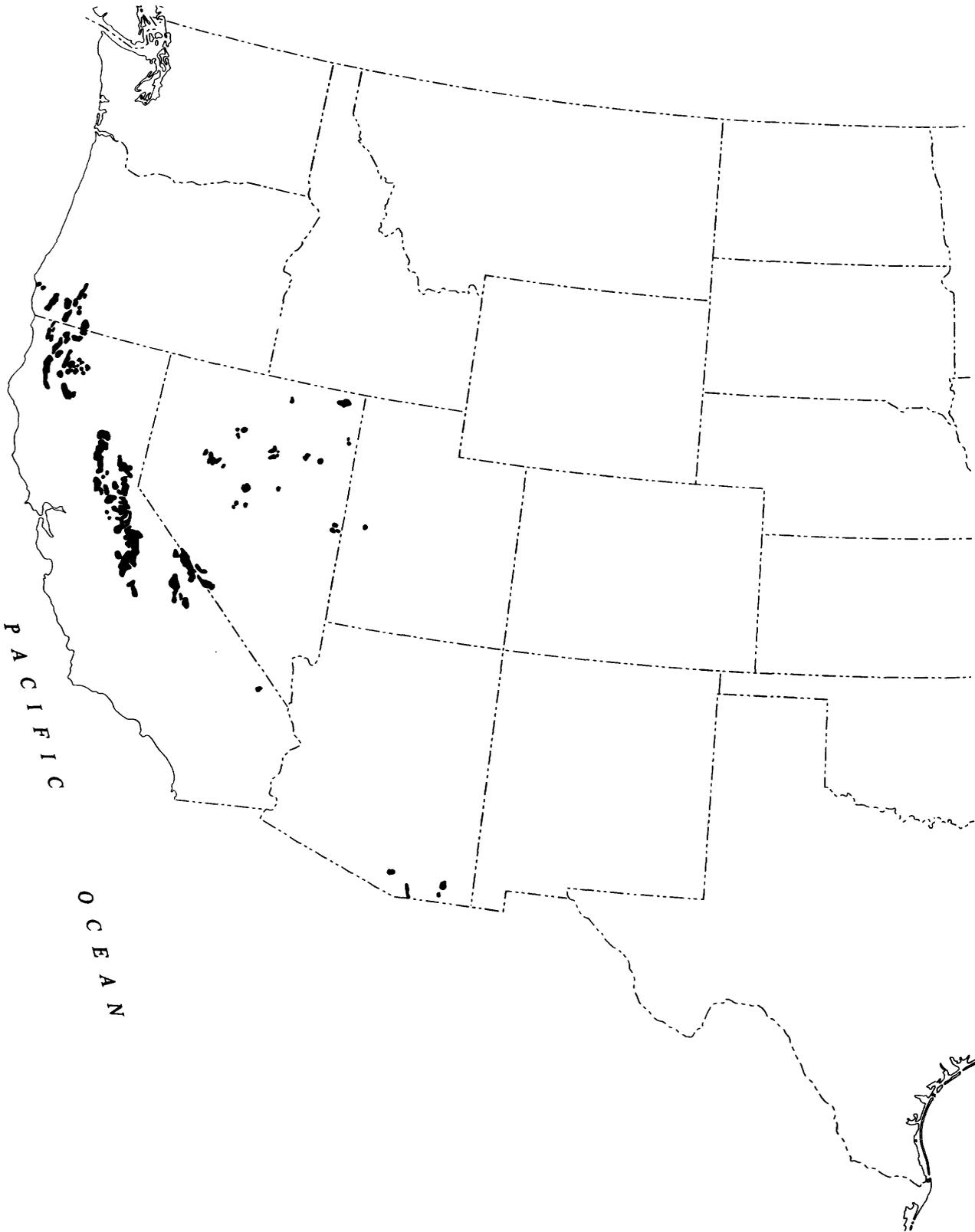


FIGURE 18.—Western United States, showing areas mapped as Jurassic granitic rocks (Jg) and mafic intrusives (Jmi) on Geologic Map of the United States.

prominent is the Conway Granite. The age of the White Mountain Series is commonly quoted as 180 m.y., or Early Jurassic, on the basis of concordant U/Pb, K/Ar, and Rb/Sr determinations on the Conway Granite (Lyons and Faul, 1968, p. 312). A wider range of sampling of the different White Mountain plutons reveals a much greater spread of ages—from 110 to 185 m.y., or from Early Jurassic into Early Cretaceous time (Foland and others, 1970). The White Mountain epoch thus overlaps that of the Monteregian intrusives in Canada to the north, which extend in a chain for 150 mi (250 km) northwestward from near the border to Montreal and which have Cretaceous ages of 84 to 123 m.y. The White Mountain and Monteregian intrusives are evidently closely related, both sequentially and magmatically.

JURASSIC MAFIC INTRUSIVES (Jmi)

In the Stillwater and West Humboldt Ranges of west-central Nevada are some areas of diorite and gabbro, which have been emplaced as tabular masses at shallow depths and are associated with basaltic lavas (Page, 1965). They have been dated by K/Ar methods at 150 m.y., or Late Jurassic.

CRETACEOUS GRANITIC ROCKS (Kg)

The dominant granitic rocks of the Cordilleran Region are of Cretaceous age. They occur throughout the length of California and into Oregon, with outlying bodies in Nevada and Arizona, and in Montana, Idaho, and Washington (fig. 19). Some of them form small to moderate-sized plutons, but in places the plutons are aggregated into large batholiths, such as the Peninsular Range batholith of southern California, the Sierra Nevada batholith farther north, and the Idaho batholith in the mountain area of central Idaho. In places, the rocks are divided on the Geologic Map according to age into Lower Cretaceous granitic rocks (Kg₁), Upper Cretaceous granitic rocks (Kg₂), and latest Cretaceous granitic rocks (Kg₃); the gneissic border rocks of the Idaho batholith are also differentiated (Kgn). Elsewhere, the Cretaceous granitic rocks are not divided (Kg).

The best known Cretaceous granitic rocks are those of the Sierra Nevada, which form a continuous body 25 mi (40 km) or more wide along the crest of the range for its entire length (Bateman and Wahrhaftig, 1966, p. 116–125). Two general times of emplacement are represented—the Huntington Lake intrusive epoch with ages of 104 to 121 m.y., or Lower Cretaceous (Kg₁), and the Cathedral Range intrusive epoch with ages of 79 to 90 m.y., or Upper Cretaceous (Kg₂), which

forms the main body (Evernden and Kistler, 1970, p. 17). The first consists of quartz diorite, quartz monzonite, and granodiorite. The second, represented by the Tuolumne Intrusive Series, includes the Sentinel Granodiorite, Half Dome Quartz Monzonite, Cathedral Peak Granite, and Johnson Granite Porphyry, and is more siliceous than the older Cretaceous and Jurassic intrusives of the Sierra Nevada. The Late Cretaceous age of the youngest granitic rocks of the Sierra Nevada raises interesting questions as to their relation to sedimentation of the Great Valley sequence, which was in progress during this time to the west. During emplacement of the batholith, the site of the Sierra Nevada was probably being raised and eroded, and the batholith surface unroofed, to provide the vast accumulation of Cretaceous sediments in the Great Valley.

Farther south is the equally large mass of the Peninsular Range batholith ("batholith of southern California"), which extends past San Diego into Mexico, where it forms the backbone of Baja California as far south as the 29th parallel (Larsen, 1954). Unlike the Sierra Nevada batholith, it was intruded during a single epoch. In the United States it cuts Upper Jurassic rocks and in Baja California cuts Lower Cretaceous rocks as young as Albian; its deeply eroded surface is overlain by undeformed Upper Cretaceous rocks of Campanian and Maestrichtian age. In southern California it has been dated by U/Pb methods as between 109 and 120 m.y., and in Baja California as between 100 and 115 m.y. (Armstrong and Suppe, 1973, p. 1385). In both areas, K/Ar dates decrease in the easternmost exposures to as little as 80 m.y., but these probably reflect cooling events related to greater depth of erosion of this part of the batholith. Like the Sierra Nevada batholith, the Peninsular Range batholith is composed of many plutons, which vary in composition from gabbro, through granodiorite and tonalite, to granite.

In the Salinian block of the Coast Ranges west of the Sierra Nevada, various granitic plutons invade the Sur Series (uP₂) and form parts of the Santa Lucia, Gabilan, and Santa Cruz Ranges, as well as the Farallon Islands, Point Reyes, and Bodega Head farther north. They include quartz diorite, adamellite, granodiorite, and granite. Dating by K/Ar methods yields ages as young as 77 m.y., but the time of intrusion is clearly older, as the eroded surfaces of the plutons are overlain by the Asuncion Group of Late Cretaceous (Campanian) age (Compton, 1966, p. 288–287). Probably this is a "cooling date," representing the time when argon could be retained in the rock, after uplift from the deep crustal level indicated by the high amphibolite and granulite metamorphic facies of the enclosing Sur

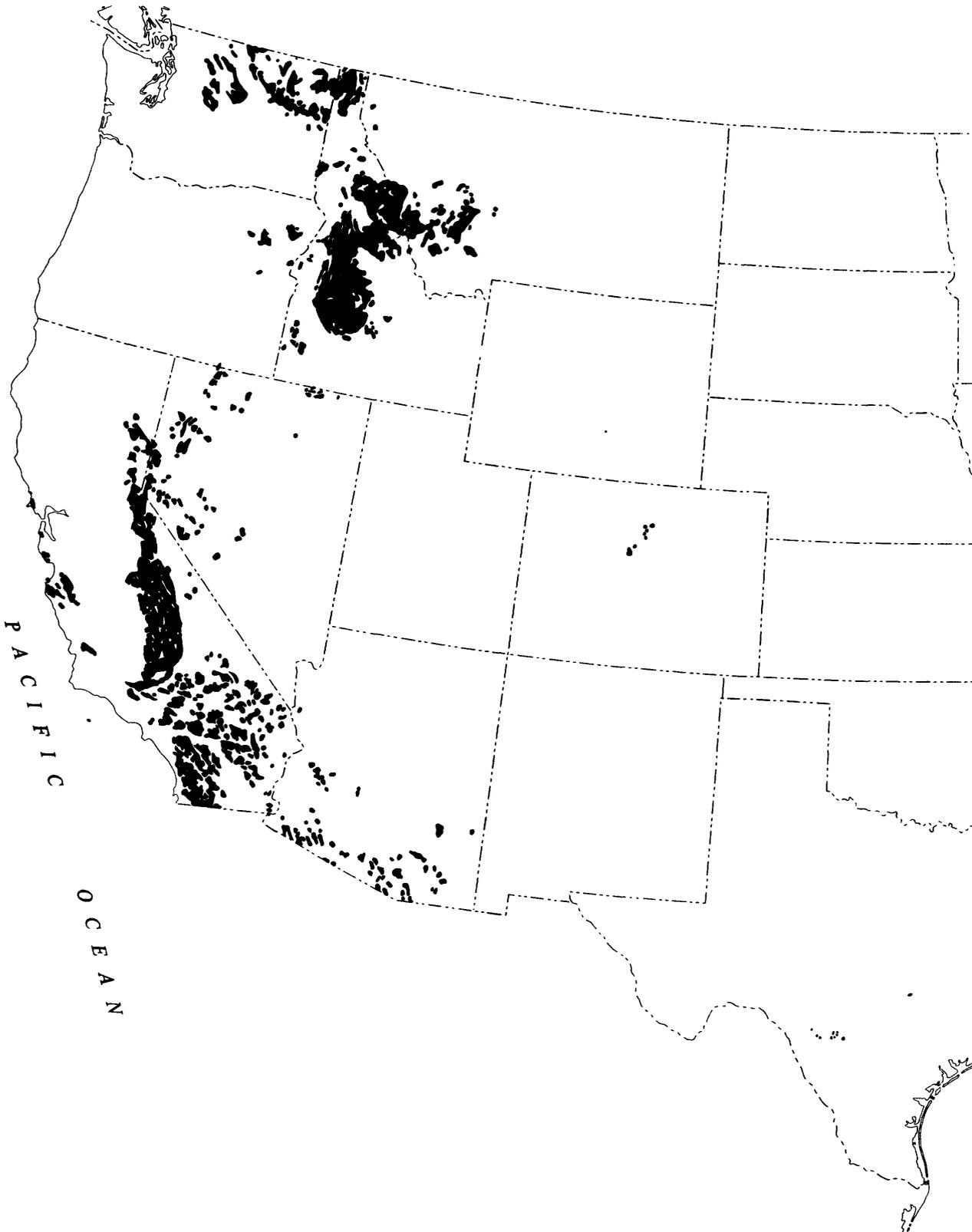


FIGURE 19.—Western United States, showing areas mapped as Cretaceous granitic rocks (Kg, Kg1, Kg2, Kg3, Kgn) and Cretaceous intrusive rocks (Ki) on Geologic Map of the United States.

Series. An Rb/Sr whole-rock date from the Santa Lucia Range of 117 m.y., or Early Cretaceous, is probably closer to the actual time of intrusion.

Similar young Cretaceous ages have been obtained from the granitic rocks of the San Gabriel and San Bernardino Mountains and probably are also "cooling dates" (Evernden and Kistler, 1970, p. 22; Armstrong and Suppe, 1973, p. 1383). Dating by U/Pb methods suggests plutonic events between 160 and 170 m.y. and 75 to 90 m.y. (Silver, 1971).

East of the Sierra Nevada in western and northern Nevada, granitic rocks form many small plutons, which are shown by radiometric dating to be partly Jurassic, partly Cretaceous, and Tertiary. The Cretaceous granites have ages of 87 to 105 m.y. and 68 to 71 m.y., approximately the same as those of the two intrusive epochs in the Sierra Nevada, (Silberman and McKee, 1971).

In the Mojave Desert region of southern California and the desert ranges of southwestern Arizona are many small to moderate-sized bodies of Mesozoic granitic rocks, which mostly yield K/Ar and U/Pb ages of 64 to 95 m.y., or Late Cretaceous, but also yield from 150 to 165 m.y. and from 190 to 200 m.y., or Jurassic and Triassic (Armstrong and Suppe, 1973, p. 1383-1384). However, the extent of the rocks of different ages is incompletely known, and except for one pluton in the Clark Mountains of the eastern Mojave Desert, all are classed as Cretaceous (Kg) on the Geologic Map.

The Idaho batholith sprawls across the mountains of central Idaho, from the Snake River Plain to northwestern Montana, with an area of about 16,000 mi² (42,000 km²) (Ross, 1936). It plunges southward beneath the Cenozoic volcanic rocks of the Snake River Plain, but it may be nearly connected in this direction with the Sierra Nevada batholith, as numerous inliers of granitic rocks emerge from beneath the Tertiary cover in southwestern Idaho and northwestern Nevada.

The Idaho batholith intrudes rocks of the Belt Supergroup (Y) on the northeast, lower and upper Paleozoic miogeosynclinal rocks (lP, uP) on the southeast, and lower Mesozoic eugeosynclinal rocks (lMze) on the southwest. It is bordered, especially on the north, by a wide zone of regional metamorphism, where parts of the Belt formations reach sillimanite grade. Most of this regional metamorphism preceded the actual emplacement of the batholith, suggesting that its site had been subjected to a considerable period of prior crustal heating (Hietanen, 1962, p. 97-99). Large inclusions in the batholith have been metasomatized and converted into gneisses that fade out into the surrounding intrusive. The oldest supra-

crustal rocks which overlie it are the Casto Volcanics (ITv) of Eocene age, and it is intruded by many small plutons of early Tertiary age (Ti).

The batholith underlies a rough wilderness area, and while parts of it have been mapped in fair detail, large parts are still poorly known or even unexplored. The surface outline of the batholith is highly irregular, with projections of granitic rocks into the surrounding country rock and many small to large inclusions or pendants of country rock within the batholith. It is nearly bifurcated near the middle by a belt of inclusions, shown on the map as metamorphosed Belt supergroup (Y), older Precambrian (Xm), and border phase of the batholith (Kgn). In this area, an eastward projection of granitic gneisses, mapped as part of the batholith, has proved from radiometric determinations to be 1,500 m.y. old, or early Precambrian Y (Armstrong, 1975, p. 440-441). The parts north and south of this belt of inclusions may be respectively termed the Bitterroot lobe and Atlanta lobe of the batholith. The batholithic rocks are mainly granodiorite and quartz monzonite. So far as is known, they do not form many individual plutons like those that characterize the Sierra Nevada and Peninsular Range batholiths; instead, large areas are of nearly uniform composition, and compositional changes from one part to another appear to be gradational. Along parts of the periphery, however, is a more mafic gneissic border phase (Kgn).

Emplacement of the batholith may have extended over a considerable period, and some rocks included with it may be much older, such as the 1,500-m.y.-old granitic gneisses mentioned above. The main period of emplacement appears, however, to have been during the Cretaceous. Radiometric determinations have yielded equivocal results, probably due in part to contamination with Precambrian materials and to updating during Tertiary plutonism. Present evidence indicates that the Atlanta, or southern lobe, has an age of about 70 to 100 m.y., or comparable to the last plutonic event in the Sierra Nevada. The Bitterroot lobe is apparently somewhat younger, with an age of about 80 m.y., or close to that of the Boulder batholith to the east (Armstrong, 1975, p. 445).

Many granitic plutons occur northwest of the Idaho batholith along the Canadian border from the Purcell Trench of northern Idaho to the northern Cascade Range of Washington State. They are the southward extensions of plutons in the western Cordillera of British Columbia. Near the Columbia River they plunge southward beneath the cover of the Miocene Columbia River lavas; they may not continue much farther, as much of the lava was probably erupted onto an oceanic crust. For the most part, the granitic rocks

are of Cretaceous age and have yielded radiometric ages close to 100 m.y., or middle Cretaceous time, although several plutons of Triassic age have already been noted and others of early Tertiary age (Ti) occur, especially toward the west. The eastern plutons invade the Belt Supergroup; others farther west lie in Paleozoic miogeosynclinal rocks of the Kootenai arc, and those beyond in Paleozoic and Mesozoic eugeosynclinal rocks (Yates and others, 1966, p. 55). They intrude eugeosynclinal rocks as young as Middle Jurassic and are overlain unconformably by plant-bearing Upper Cretaceous rocks, but abundant granitic debris first appears in Eocene conglomerates.

East of the Idaho batholith in western Montana is an array of younger Cretaceous granitic plutons, of which the largest and best known is the Boulder batholith. They are classed on the Geologic Map as "latest Cretaceous granitic rocks" (Kg₃) and are commonly referred to as "Laramide" intrusives. Emplacement of these granitic rocks overlaps in time that of the Upper Cretaceous granitic rocks (Kg₂) of the Sierra Nevada; however, this emplacement continued later, and the associations of the two sets of rocks are quite different.

The Boulder batholith extends north-northeast transverse to the regional trends of the enclosing rocks, with an area of about 2,300 mi² (5,700 km²) and a length of about 60 mi (100 km) (Robinson and others, 1968). It invades the Belt Supergroup and the Paleozoic and Mesozoic rocks as young as the Elkhorn Mountain Volcanics (Kv) of Campanian age; it is overlain unconformably by the middle Eocene Lowland Creek Volcanics (ITv). The batholith is a composite mass of a dozen or more plutons of calc-alkalic rocks which range in composition from syenogabbro to alaskite but are dominantly quartz monzonite and granodiorite. Nearly three-fourths of the batholith was emplaced between 71 and 82 m.y., and thus it partly overlaps the eruption of the Elkhorn Mountain Volcanics (73 to 78 m.y.), as well as the thrust faulting of the country rocks which occurred during Campanian and Maestrichtian time (approximately between 66 and 80 m.y.).

The mode of emplacement and the structure of the batholith remain controversial. Was it a steep-walled intrusive, descending into the depths from its roof of Elkhorn Mountain Volcanics (Klepper and others, 1971, p. 1580)? Or was it a shallow floored body that was open to the sky, on whose surface the Elkhorn Mountain Volcanics congealed as a sort of slag (Hamilton and Myers, 1967, p. C6-C9)? Probably the truth lies somewhere between these two extremes.

Another group of "Laramide" plutons (Kg₃) of smaller individual dimensions is in the Mineral Belt of Colorado, mostly in the Front Range (Tweto, 1968, p.

564-565). They have yielded radiometric ages of about 60 to 70 m.y., and clasts derived from them have been identified in the Paleocene deposits of the Denver basin to the east. These plutons are part of a chain of intrusive rocks that extends southwestward along the Mineral Belt past the San Juan Mountains, but most of those west of the Front Range are younger, of early Tertiary age (Ti).

Other "Laramide" granitic rocks (Kg₃) occur in southern Arizona, partly intermingled with but mostly to the east of the earlier Mesozoic granitic rocks (Jg, Kg) (Armstrong and Suppe, 1973, p. 1385).

CRETACEOUS INTRUSIVE ROCKS (Ki)

Small bodies of intrusive rock of Cretaceous age occur at the inner edge of the Gulf Coastal Plain in southwestern Arkansas and central Texas, associated with tuffaceous rocks interbedded in the Upper Cretaceous marine sequence.

Southeast of Little Rock in Arkansas, two sizeable knobs of nepheline syenite project through the early Tertiary deposits of the Midway and Wilcox Groups, which contain their weathered products, including commercial deposits of bauxite (Gordon and others, 1958, p. 60-71). A little farther west, in the folded Paleozoic rocks of the Ouachita Mountains, are numerous plugs of similar rock, of which the largest and best known is that at Magnet Cove, and many satellitic dikes. About 80 mi (130 km) to the southwest, at the edge of the Coastal Plain near Murphreesboro, four small pipes of diamond-bearing peridotite cut the Lower Cretaceous Trinity Group (Miser and Purdue, 1929, p. 99-117), containing the only abundant diamonds in the United States. Genetically related to the intrusive rocks are beds of volcanic tuff and tuffaceous sandstone in the lower part of the Upper Cretaceous in the same area—the Woodbine Sand (uK₁) and the Tokio Formation of Austin age (uK₂)—some of which are as much as 125 ft (40 m) thick (Ross and others, 1929).

In central Texas, near the Balcones fault zone at the edge of the Coastal Plain, another group of Cretaceous intrusive rocks extends from Austin 150 mi (250 km) westward past Uvalde (Lonsdale, 1927, p. 9-46). They are small plugs and laccoliths of nepheline basalt and phonolite, which intrude Cretaceous rocks as young as the Austin and Taylor Formations, or somewhat higher than the intrusive and volcanic rocks in Arkansas. As in Arkansas, the associated marine deposits of the Austin and Taylor contain much volcanic debris, as well as several layers of bentonite. The Pilot Knob intrusive near Austin has sometimes been referred to as a fossil volcano, for which there is some support in the

abundant volcanic debris in the surrounding Austin and Taylor Formations. Nevertheless, the intrusive rocks everywhere cut these formations, indicating a younger age. It has been postulated that there were two periods of igneous activity in the district, one during Late Cretaceous and another in early Tertiary time (Lonsdale, 1927, p. 44-46), but the interval between them need not have been great; it seems more likely that all the igneous rocks are of Late Cretaceous age, as represented on the atlas sheets of the new Geologic Map of Texas (Austin and San Antonio sheets, 1974), and this assignment is followed on the Geologic Map.

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