The Cenozoic Rocks; a Discussion to Accompany the Geologic Map of the United States

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By PHILIP B. KING and HELEN M. BEIKMAN

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THE CENOZOIC ROCKS: A DISCUSSION TO ACCOMPANY THE GEOLOGIC MAP OF THE UNITED STATES

By Philip B. King and Helen M. Beikman

ABSTRACT

The Cenozoic rocks formed during the last 65 million years of geologic time and, being the last to form, still cover nearly half the country. They are a varied and complex assemblage, including marine stratified rocks near the present Atlantic, Gulf, and Pacific coasts, continental deposits in the interior region, and volcanic rocks through much of the western Cordillera.

The marine stratified rocks in the east form most of the Atlantic and Gulf Coastal Plains and range in age from Paleocene to Pliocene. They are the thin updip edges of deposits that thicken in subsurface toward the coasts and are largely shallow-water marine deposits, with marginal brackish-water and continental phases, that change downdip in subsurface into deeper-water marine deposits.

The marine stratified rocks in the California segment of the Pacific coast likewise range in age from Paleocene to Pliocene and Pleistocene, but they are thicker, more varied, and more complex and have been more heavily involved in orogenic deformation. As a result, they do not lie in regionally consistent belts of outcrop but form numerous sedimentary basins of different ages. They include not only shallow-water marginal deposits and fringing continental deposits, but nearer the coast deep-water deposits that were laid down beyond the edge of the continent of the time.

The marine stratified rocks of the Pacific coastal segment to the north, in Oregon and Washington, are mainly of Eocene, Oligocene, and Miocene age. Like their counterparts farther south, they range from near-shore and continental deposits on the east, to deep-water deposits farther west, but they differ in their much greater volcanic component, including submarine pillow lavas, terrestrial lavas, and a large volcanic-derived content in all the sediments.

Continental deposits of Cenozoic age are especially prominent in the Rocky Mountains and adjacent Great Plains and range in age from Paleocene to Pliocene. The Paleocene and Eocene deposits fill to great thickness basins between the newly raised mountain uplifts and east of the mountains. They are mostly flood-plain and swamp deposits but include some extensive deposits laid down in lakes, represented by the Paleocene Flagstaff Limestone and the Eocene Green River Formation. The Oligocene, Miocene, and Pliocene deposits are thinner, but they are even more extensive east of the Rocky Mountains, where they spread as great sheets across the Great Plains that were laid down by streams carrying detritus derived from erosion of the mountains to the west.

The Quaternary deposits are only partly represented on the Geologic Map. Not shown, for example, are the glacial drift and associated deposits that are extensive in the northern states. Quaternary deposits are shown only where they are an essential feature of the bedrock pattern and attain sizeable thickness, as in the Mississippi Embayment, the Atlantic and Gulf Coastal Plains, and the intermountain basins in the west.

Volcanic rocks of Cenozoic age occur throughout the western Cordillera, but they form an especially thick, continuous blanket in the northwestern States of Washington, Oregon, and Idaho. All ages are represented, from Eocene to Quaternary.

The lower Tertiary (Eocene and Oligocene) volcanic rocks are less widely exposed than the younger ones. They are dominantly of andesitic or intermediate composition. They include the marine pillow basalts of the Coast Ranges of Oregon and Washington that are interbedded in the Eocene strata and the lower Tertiary andesites of the Cascade Range not far to the east. Farther east are some notably thick and extensive volcanic fields, as in the Absaroka Mountains of northwestern Wyoming, the San Juan Mountains of southwestern Colorado, and the Mogollon Plateau of southwestern New Mexico.

The upper Tertiary (Miocene and Pliocene) volcanic rocks are more extensively exposed and of more diverse compositions. They include the upper Tertiary andesites of the Cascade Range and the great mass of tholeiitic plateau basalts of the Columbia River Group in the Columbia Plateau. Farther south, in the Great Basin, is an extensive body of felsic volcanic rocks, mainly ash-flow tuffs or ignimbrites that spread as broad sheets across the featureless terrane prior to its disruption by Basin and Range block-faulting. Smaller areas of upper Tertiary volcanic rocks occur throughout the remainder of the Cordillera, but notably along the southwestern and southern edges of the Colorado Plateau.

Quaternary volcanic rocks have a much smaller distribution and are restricted to areas that remained tectonically active in recent times. They include the chain of andesitic volcanoes on the crest of the Cascade Range from Washington, through Oregon, into northern California; and a transverse belt of basaltic volcanics that extends along the Snake River Plain of southern Idaho and into southeastern Oregon. Basaltic flows occur in many other areas; in addition there are a few notable centers of felsic volcanism—in Yellowstone National Park, along the eastern side of the Sierra Nevada, and in the Jemez Mountains of New Mexico.

Tertiary intrusive rocks form much smaller areas in the western Cordillera than those of Mesozoic ages and are of diverse ages and habits. They include many small hypabyssal stocks and laccoliths, but there are a few larger masses of deep-seated origin and batholithic dimensions. The latter are especially prominent in the northern Cascade Range of Washington, the region of the Idaho batholith in Idaho, and the Southern Rocky Mountains of Colorado.

INTRODUCTION

This is the last of a series of four reports dealing with features shown on the Geologic Map of the

United States (1974). Professional Paper 901 deals with general principles and problems relating to the map; Professional Paper 902 with the Precambrian rocks; Professional Paper 903 with the Paleozoic and Mesozoic rocks; and Professional Paper 904 (the present report) with the Cenozoic rocks.

The Cenozoic rocks formed only during the last 65 million years of geologic time, but, being the youngest, they spread over nearly half the country. They are a varied and complex assemblage, including marine stratified deposits along the Atlantic, Gulf, and Pacific coasts, continental deposits in the interior region, and volcanic rocks in the western Cordillera. The Cenozoic rocks in the eastern half of the country are flat-lying or gently tilted, but those in the western half have been mildly to strongly deformed by various orogenies during Cenozoic time.

The treatment of the Cenozoic rocks in the present account, as in the account of the Paleozoic and Mesozoic rocks, closely follows the outline of the map legend. The rocks of successive ages are treated in turn, from Paleocene to Holocene. Under each category, the first rocks described are the marine strata, in geographic order from east to west, and next the continental deposits; a small body of eugeosynclinal deposits of early Tertiary age is treated separately. Following this, the Cenozoic volcanic rocks are dealt with, again by successive ages, from one area to another. In a final section, the Tertiary intrusive rocks are treated briefly.

The report is illustrated by a series of maps showing the surface extent of the rocks of different ages (figs. 1-7, 12, 13, 15, 16), as they are represented on the Geologic Map of the United States. In addition, a few figures are included that show special features of the volcanic rocks that are not brought out clearly on the Geologic Map.

The Cenozoic is conventionally divided into the Tertiary and Quaternary Systems, the first being much the greater, the second only representing the last 2 million years of geologic time. The Tertiary is in turn divided into the Paleocene, Eocene, Oligocene, Miocene, and Pliocene Series, and the Quaternary into the Pleistocene and Holocene Series. The Quaternary is distinguished from the Tertiary mainly by its glacial periods—although this climatic regime, in fact, actually began during the later Tertiary.

The Cenozoic Era succeeded the great orogenies of later Mesozoic time—although orogenic deformation continued into the Cenozoic and continues even today in some areas. The Mesozoic orogenies produced a major reorganization of the continent, so that it became more widely emergent than ever before. The great epicontinental seas of previous eras were permanently expelled from most of the continent, so that during the Cenozoic marine deposits were laid down only near the present coasts. Continental deposits continued to be laid down in some of the interior areas, but other areas, such as much of the eastern interior, became permanent land surfaces. The emergent regime of the Cenozoic resulted in quickening of erosional processes, so that great quantities of clastic detritus were eroded from the land and delivered to the areas of sedimentation that remained. Another result of the Mesozoic orogenies in the western Cordillera was the subsequent increase in volcanic activity, resulting in extensive fields of lavas, pyroclastic rocks, and volcaniclastic sediments being spread over much of the Western States during the Cenozoic.

TERTIARY SYSTEM

PALEOCENE AND EOCENE SERIES

The Paleocene and Eocene Series formed during a span of about 28 million years, or the first third of Tertiary time. In terms of the standard European sequence, the Paleocene corresponds to the Danian, Montian, and Thanetian Stages; and the Eocene to the Ypresian, Cuisian, Lutetian, Auversian, Bartonian, and Ludian Stages. As explained below, several schemes of stages have been used for local purposes in the marine sequence in California, and another set of stages is used for the North American continental Tertiary.

Although the Paleocene and Eocene Epochs occupied a sizeable fraction of Tertiary time, the rocks of these epochs are considered together in this account. In some places, as in the Rocky Mountain region, the two sets of deposits are considerably different, because they formed in different depositional basins. In other places, however, the distinctions are less marked, and there is controversy as to the boundary between the two series.

The Paleocene and Eocene are represented on the Geologic Map of the United States by stratified sedimentary rocks, mostly marine (Tx, Te); by continental deposits (Txc, Tec); and by eugeosynclinal deposits (Tee). In the Gulf Coastal Plain, the Eocene stratified rocks are separated into three divisions (Te1, Te2, Te3), which correspond to the Wilcox, Claiborne, and Jackson Groups. In parts of the Rocky Mountain region, Eocene lacustrine deposits (Tel) are differentiated amidst the continental deposits. Eocene volcanic rocks in the Western States are mostly grouped in the lower Tertiary volcanic rocks (lTv), which are discussed separately later. However, in the Coast Ranges of Oregon and Washington, Eocene pillow basalts (Teb) are separately mapped.

Paleocene and Eocene rocks cover sizeable areas—perhaps as much as 10 percent of the area of the Forty-eight States shown on the Geologic Map (fig. 1). They form a broad outcrop belt along the inner part of the Gulf Coastal Plain, and smaller, more discontinuous areas in the same position in the Atlantic Coastal Plain. The most extensive outcrop areas of Paleocene and Eocene rocks are, however, in the Rocky Mountain region and northern Great Plains, where they form the centers of basins between the mountain uplifts. Along the Pacific Coast, Paleocene and Eocene rocks are recognized from southern California to northwestern Washington, but because of the considerable deformation to which they have been subjected, individual outcrops are small and discontinuous.

MARINE STRATIFIED ROCKS

GULF COASTAL PLAIN[1]

The Paleocene and Eocene Series are exposed in belts around the inner half of the Gulf Coastal Plain. The outcropping rocks are the updip edges that extend in subsurface toward the Gulf, where they form a thick, relatively unbroken, dominantly argillaceous marine sequence. The exposed rocks, to which main attention is given here, are thinner, more interrupted, more coarsely clastic deposits, that were laid down in marine, littoral, and continental environments along the edge of the continent.

MIDWAY GROUP (Tx)

The Midway Group at the base of the Tertiary coastal plain sequence was named in 1887 for Midway Landing on the Alabama River in Alabama. The group crops out in a nearly continuous band from the Rio Grande in Texas to Georgia, with a notable deflection northward to southern Illinois in the Mississippi Embayment. Exposed sections of the Midway are generally less than 500 ft (150 m) thick. In most places the Midway can be divided into two or more formations. Eastward from Georgia, the Midway is overstepped by succeeding Eocene formations.

In contrast to parts of the succeeding Eocene sequence, the Midway is marine throughout; in places it much resembles the uppermost Cretaceous deposits on which it lies, although with a notably different fauna. The Midway is a subtropical, warm-water deposit, whose fauna also differs from apparently correlative strata elsewhere, as in western Europe and on the Pacific Coast. It is commonly considered to be the sole representative of the Paleocene in the Gulf Coastal Plain, but accumulating paleontological evidence suggests that the top of the Paleocene extends somewhat higher in terms of the European standard sections (see below).

In Texas the Midway is divided into the Kinkaid and Wills Point Formations, the first of glauconitic sands and clays with several lenses of coquinid limestone, the second largely clay and silty clay of a deeper water facies. In Mississippi and Alabama it is divided into the Clayton Formation, Porters Creek Clay, and Naheola Formation. The Clayton somewhat resembles the Kinkaid, being glauconitic, sandy, and limy, and the Porters Creek the Wills Point, being dark laminated clay. The Porters Creek extends northward beyond the remainder of the group into southern Illinois. The Naheola differs from the others in being sandy and noncalcareous.

On the crest of the Sabine uplift, south of the main outcrop belt, in northwestern Louisiana and eastern Texas, a large circular area of outcrop was formerly mapped as Midway but is now interpreted as a marine downdip argillaceous facies of the Wilcox Group and is so represented on the Geologic Map. Only a small outcrop in the north part of the uplift, northwest of Shreveport, is now considered to be of Midway age.

WILCOX GROUP (Tel)

The Wilcox Group, or initial Eocene unit of the Gulf Coastal Plain, was named in 1906 for Wilcox County, Alabama, to replace the previously used lithologic term "lignitic." The term Sabine was proposed at about the same time for the same unit west of the Mississippi and is still used by some geologists in Louisiana. The Wilcox forms an interrupted band of outcrop in the inner part of the Gulf Coastal Plain in Texas eastward to Georgia, where it is cut off by overstep of younger Eocene units. As indicated above, the Wilcox is also exposed in a large area on the crest of the Sabine uplift in northwestern Louisiana and eastern Texas. On the outcrop the Wilcox is as much as 1,000 feet (300 m) thick. In large parts of its outcrop (for example, in Texas and the Mississippi Embayment) the Wilcox is of nonmarine facies and is indivisible in many areas. In other places, however, intertonguing marine strata permit subdivision of the group into formations, which vary from one region to another.

In central Texas the Wilcox Group was divided by Plummer (1932, p. 574) into the thick medial nonmarine Rockdale Formation of sands, clays, and

[1]A general review of the Paleocene and Eocene formations of the Gulf Coastal Plain is presented by Murray (1961, p. 367–394). For an earlier more detailed summary of the Texas segment, see Plummer (1932, p. 531–699).

FIGURE 1.—Map of the United States showing surface distribution of Paleocene and Eocene rocks as represented on the Geologic Map of the United States (units Tx, Txc, Te, Tec, Tel, Tee, Teoe).

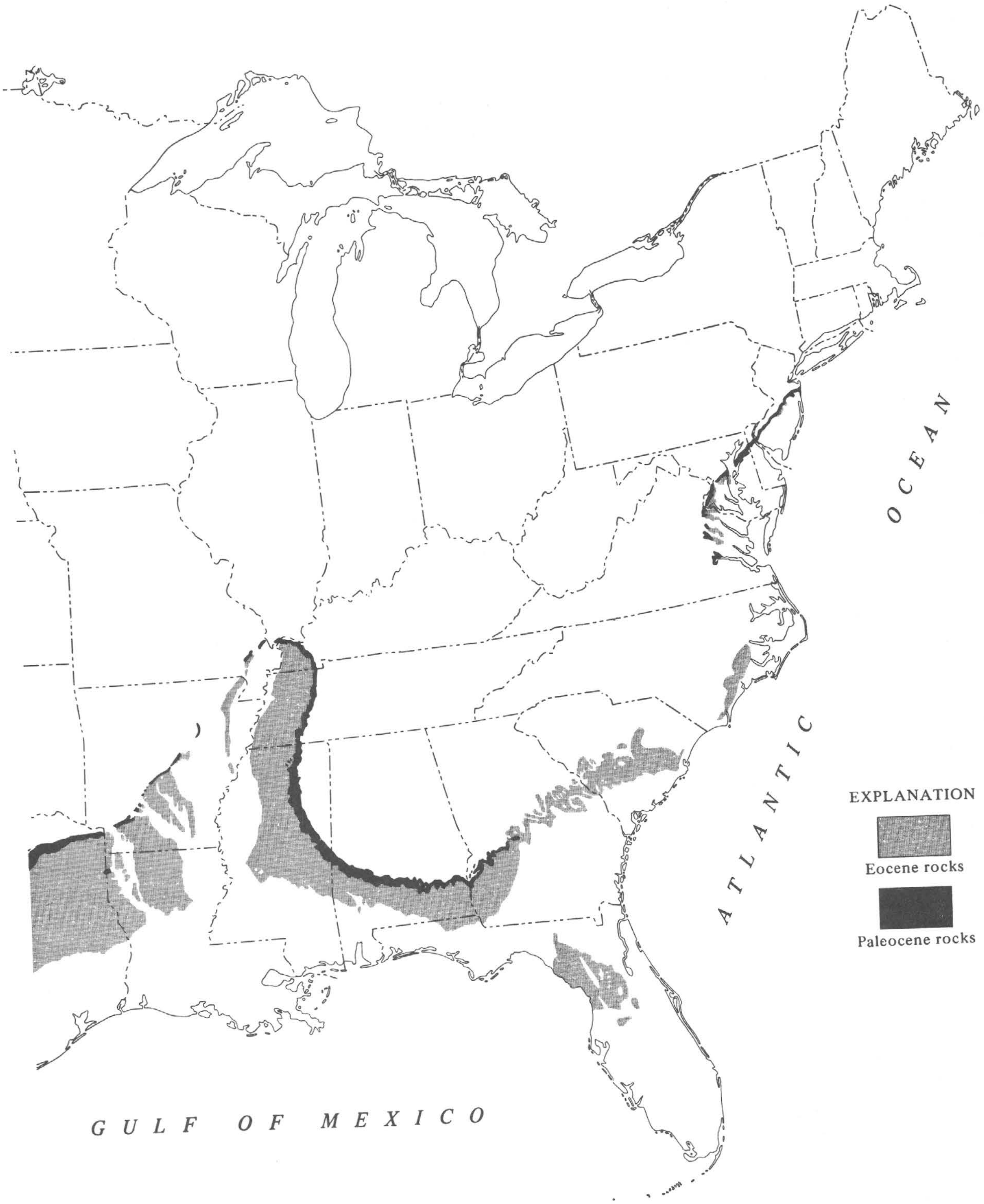

FIGURE 1.—Continued.

lignites, underlain and overlain by thin fossiliferous marine units, the Seguin and Sabinetown Formations. In later work (as shown on the Waco and Austin sheets of the Texas Geologic Atlas, 1970, 1974) the same sequence of nonmarine beds is divided into the Hooper Formation below, the medial-sandy Simsboro Formation (classed as a member by Plummer), and the Calvert Bluff

Formation above; the marine units are not mentioned. Farther southwest in Texas, the undivided Wilcox has traditionally been termed the Indio Formation.

In Alabama, Mississippi, and Georgia the nonmarine beds of the Wilcox are principally in its upper part, and the group is divided into the Nanfalia, Tuscahoma, and Hatchetigbee Formations (with the Bashi Marl Member at the base of the latter). Planktonic foraminifers indicate that the Paleocene-Eocene boundary, in terms of European standard sections, is above the boundary between the Midway and Wilcox Groups (Berggren, 1965, p. 280–282). On the basis of these foraminifers the Bashi Marl of Alabama is basal Eocene (Ypresian). The Nanfalia Formation (and the local Salt Mountain Limestone) are upper Paleocene (Sparnacian). The overlying Tuscahoma Formation and the Seguin Formation of Texas do not contain planktonic foraminifers suitable for long-range correlations but are presumed to be upper Paleocene.

This creates problems of representation on the Geologic Map, where the units adopted are the Midway and Wilcox Groups, which are assigned to Paleocene and Eocene ages, respectively. It seems fruitless to attempt to subdivide the Wilcox on the basis of these new judgements, as the Paleocene-Eocene boundary in the Wilcox is certainly known only in the relatively complete marine sequence in Alabama. Elsewhere, much of the Wilcox is nonmarine and is generally undivided on the source maps. We consider it best to leave the boundaries where they are, pending the receipt of other data, with the understanding that part of the Wilcox is actually Paleocene.

At the eastern end of the Eocene outcrop belt, in South Carolina, equivalents of the Wilcox reappear in a small area from beneath the overlap of the younger formations and are known as the Black Mingo Formation. The Black Mingo contains some of the marine mollusks which occur in the Nanfalia and Tuscahoma Formations of Alabama, as well as some others that are more characteristic of the Midway Group in that area, so that the Black Mingo evidently contains undifferentiated strata of both early Eocene and Paleocene age (Cooke and MacNeil, 1952, p. 20–21).

CLAIBORNE GROUP (Te2)

The Claiborne Group was named in 1847 for Claiborne Bluff on the Alabama River in Alabama. It is perhaps 1,000 feet (300 m) or more thick, and because of its thickness and various structural complications it has a much larger outcrop area than any of the other Paleocene or Eocene units, especially in the Mississippi Embayment and west of the Mississippi River. In south Texas it forms an outcrop band 60 miles (95 km) or more broad in the Rio Grande embayment, and in northeast Texas it occupies most of the East Texas embayment and extends around the north and south sides of the Sabine uplift into southern Arkansas and northern Louisiana, where its outcrop is 120 miles (190 km) broad. It also underlies all the northern two-thirds of the Mississippi Embayment as far north as Illinois, although its outcrops are interrupted in part by downfolds of Jackson Group (Te3) and by Quaternary deposits. East of the Mississippi River it forms a narrower band of outcrop that extends eastward across Georgia and South Carolina, beyond the truncated edges of the Midway and Wilcox Groups.

The Claiborne is notable for its highly fossiliferous marine strata, whose fossils have been extensively collected and investigated for years, since the days of the early geological explorers. Its deposits characteristically form a series of cyclical sequences, each beginning with transgressive glauconitic, calcareous, fossiliferous strata; passing up into dark argillaceous deeper-water deposits; and terminating with regressive carbonaceous to lignitic sandy and argillaceous deposits.

In Alabama the Claiborne is divided into the Tallahatta Formation, the Lisbon Formation, and the Gosport Sand. The Tallahatta is one of the more resistant units of the Gulf Coastal Plain and forms a prominent cuesta, as its sands and clays are indurated on the outcrop to "buhrstone," which was used in the early days for millstones. The Gosport is the most fossiliferous of the three units; its fossils were first described by Conrad as early as 1833.

In Texas the Claiborne Group is divided into the Carrizo Sand, the Mount Selman Formation (with the Reklaw, Queen City, and Weches Members), the Cook Mountain Formation (with the Sparta and Crockett Members), and the Yegua Formation. The units are all widely recognizable, and they or their equivalents have been mapped across Texas and into Louisiana. The Carrizo at the base is continental and is a sheet of sand that was spread widely along the shore. The Yegua at the top is again of continental or brackish water facies. The intervening units are mainly marine or littoral. The Weches Member is the most prominently exposed unit and forms escarpments and mesas. It is highly glauconitic and its weathered surfaces are deeply encrusted with brown iron ore that has been exploited commercially from time to time (Eckel and Purcell, 1934, p. 482–503).

In eastern Georgia and in South Carolina the Claiborne Group is represented by the McBean Formation, 100 feet (30 m) or so thick, and approximately equivalent to the Lisbon and Mount Selman Formations of the Claiborne Group farther west.

JACKSON GROUP (Te3)

The Jackson Group, or highest Eocene unit in the Gulf Coastal Plain, was named in 1856 for Jackson, Mississippi. The group is 500 feet (150 m) or more thick, and forms a nearly continuous band of outcrop in the middle of the coastal plain from the Rio Grande in Texas to South Carolina. Several large outliers of the Jackson occur in downwarps in the Mississippi Embayment as far north as Kentucky, and a large inlier emerges on the crest of the Ocala uplift in northwestern Florida.

Strata of the Jackson Group were deposited during a separate and widespread marine transgression in the Gulf region. In the eastern part of the region the deposits are mainly calcareous, in the central part argillaceous, and in the western part sandy.

In Texas the Jackson was formerly grouped as the Fayette Formation, but its sandstone and clay units are widely traceable, and it is now divided into the Caddell, Wellborn, McElroy, and Whitsett Formations, with various members (Eargle, 1959). The sediments are rich in volcanic detritus and contain many deposits of commercially exploitable bentonite and fuller's earth (King, 1940, p. 170–178). In south Texas the upper, or Whitsett Formation, also contains large uranium deposits that have been mined since 1960 (Eargle and others, 1975).

In the central, or type area, near Jackson, Mississippi, the Jackson consists of the Moodys Branch Marl, a glauconitic, sandy and shaly deposit; and the Yazoo Clay, a dominantly argillaceous deposit. Northward in the Mississippi Embayment marine components fade out and the group becomes largely clastic and continental. Calcareous components increase southeastward, and in Florida the group is represented by the solid body of the Ocala Limestone, poorly to well indurated and crowded with foraminifers, bryozoans, mollusks, and echinoids. In northwestern Florida the Ocala is an important aquifer and is the source of many large springs.

ATLANTIC COASTAL PLAIN

Except for the Castle Hayne Formation of eastern North Carolina (of Claiborne and Jackson age) no Paleocene or Eocene rocks are exposed for 250 miles (400 km) north of South Carolina. The next Paleocene and Eocene outcrops are in the segment in northern Virginia, whence they continue to the terminus of the Coastal Plain in northeastern New Jersey. The rocks form a narrow band of outcrop next to the Cretaceous, which is overstepped in places by Miocene deposits.

The Paleocene and Eocene deposits in this region are not more than a few hundred feet thick on the outcrop and are all shallow-water marine deposits. The rocks are highly fossiliferous in places and are composed mostly of glauconitic sands and clays; however, some more calcareous units occur. The Paleocene is represented in Virginia and Maryland by the Aquia Formation, and in New Jersey by the Hornerstown and Vincentown Formations. The overlying Eocene deposits, largely of Wilcox age, are more discontinuous in outcrop because of Miocene cover. In Virginia and Maryland the Eocene comprises the Nanjemoy Formation, and in New Jersey the Manasquan Formation.[2]

PACIFIC COASTAL AREA

Marine stratified Paleocene and Eocene rocks are exposed along the entire length of the Pacific coastal belt from southwestern California to northwestern Washington, and in places attain thicknesses of more than 10,000 feet (3,000 m). Because the rocks have been subjected to greater deformation than in the Gulf and Atlantic coastal areas, individual outcrops are smaller and more discontinuous, especially in California where folding and faulting have been greatest. The largest and most continuous outcrop area is in the Coast Ranges of western Oregon and Washington, where folding is relatively open.

Throughout the length of the Pacific coastal belt the Paleocene and Eocene deposits exhibit a westward transition across a zone 80 to 120 miles (125-190 km) wide. They grade from nonmarine continental deposits on the east, through shallow-water, nearshore deposits, to deep-water deposits, mainly formed on deep-sea fans. However, this pattern varies considerably from place to place, and in California the original geographic pattern has been much disordered by large strike-slip movements along the San Andreas and other faults. In the Olympic Mountains of northwestern Washington, some deposits are differentiated as "eugeogeosynclinal" and separately mapped (Tee).

[2]Many details of these units are given by Spangler and Peterson (1950, p. 52-61, 72-75). Their planktonic Foraminifera are discussed by Loeblich and Tappan (1957, p. 1127-1132).

Distinctions between deposits of Paleocene and Eocene ages are unclear in many areas, partly because of the scantiness of fossils, the equivocal nature of the faunas, and uncertainty of correlation with type Paleocene and Eocene. Paleocene marine deposits are differentiated on the map in California where they have been identified with certainty; elsewhere, both here and farther north, the Paleocene, if present, is not separated from the more extensive Eocene deposits.

CALIFORNIA[3]

The paleontology of the Paleocene and Eocene marine rocks of California has been intensively studied for many years and has produced several sets of stages that are in common use. Using the larger invertebrate fossils, the Paleocene has been divided into the Martinez and Meganos Stages, and the Eocene into the Capay, Domengine, transition, and Tejon Stages. On the basis of benthonic Foraminifera, the Paleocene has been divided into the Ynezian and Bulitian Stages, and the Eocene into the Penutian, Ulatisian, and Narizian Stages (Mallory, 1959). Many of the first set of names were derived from formations in local areas, and in older reports they were used as formation names in wide areas in California. This usage is now outmoded, and the names are used as formations only in places in or near where they were first defined, other names being substituted in other areas where the rocks are of different facies although of approximately similar age. Correlation of the California Paleocene and Eocene units with units of these ages on the Gulf coast is rather vague, although some similarity of foraminiferal species in the two areas has been noted.

Northeastern California, the region northeast of the San Andreas fault and north of the Tehachapi Mountains, is less disrupted tectonically than in the rest of the State, hence best preserves the original pattern of the Paleocene and Eocene deposits.

In the western foothills of the Sierra Nevada, the lower Eocene Ione Formation (Tęc) overlaps the Mesozoic basement. Except for a few marine intercalations, the Ione is a continental deposit as much as 1,000 feet (300 m) thick; it is composed of sandstone members, some beds of lignite, and members of remarkably pure kaolinitic clay that formed during a time of deep chemical weathering of the bedrock in a tropical climate. The Ione is more or less confluent with the ancient river channel deposits on the slopes of the Sierra Nevada to the east (the "Auriferous Gravels"). A somewhat similar continental deposit, the Montgomery Creek Formation, crops out along the western edge of the Cascade Range farther north, lying unconformably on the basement rocks of the Klamath Mountains to the west, and passing eastward beneath the Pliocene lavas of the Cascade Range.

The Eocene deposits change rapidly into marine facies when traced in subsurface beneath the Great Valley. On its western side, in the Diablo Range and north of San Francisco Bay, the Paleocene and Eocene still consist of deposits that were mostly laid down in waters of moderate depth. Nevertheless, drilling in the Great Valley has revealed several deep gorges or submarine canyons which slope westward from the Sierra Nevada and are filled with deeper-water deposits. The most impressive is the Markley gorge in the latitude of Sacramento, formed during the late Eocene and Oligocene.

On the east slope of the Diablo Range near Mount Diablo, the exposed sequence is about 9,000 feet (2,750 m) thick above the Upper Cretaceous and is divided into the Martinez Formation, the Meganos Formation, Capay Formation, Domengine Sandstone, and the Nortonville Shale Member of the Kreyenhagen Formation. Except for the Nortonville, all the units are prevailingly sandy and contain conglomerate; the sediments were mainly derived from the Sierra Nevada to the east.

Accumulating evidence suggests that Late Cretaceous and early Tertiary movements had occurred along the San Andreas fault (or its ancestor), so that the Salinian block of basement rocks already projected some distance northward along the west side of the San Joaquin Valley, producing a shallow embayment. As a result, some of the sandstones of the southern area were derived from western sources and contain Franciscan and Salinian detritus.

In the northern Coast Ranges, occasional outliers of Paleocene and Eocene rocks of Great Valley-type occur within the Franciscan terrane, but they are parts of klippen that have been carried westward along the Coast Range thrust. A quite different facies forms a part of the "coastal belt" of the Franciscan assemblage (Ke of map) and is shown by fossils to be of Paleocene and Eocene ages (Evitt and Pierce, 1975). It is less disordered than the main body of the Franciscan assemblage and probably formed during the waning stages of the Franciscan deep-sea trench.

In the Eureka district along the coast farther

[3]For a general summary, with emphasis on the sedimentology, see Nilsen and Clarke (1975). Data on southern California are given by Durham (1954), on the Great Valley by Haeckel (1966, p. 223-230), and on the Coast Ranges of central and northern California by Page (1966, p. 263-266). Interesting early summaries, now largely outmoded, were presented by Reed (1933, p. 120-146), and by Reed and Hollister (1936, p. 17-27).

north, the Franciscan is overlain by the Yeager Formation (Tx), a fossiliferous shallow-water deposit, also classed as of Paleocene age, which is evidently a near-shore facies of the upper part of the "coastal belt" Franciscan.

The rocks southwest of the San Andreas fault were shifted by strike-slip movements at least 400 miles (650 km) northwestward between early Tertiary and Quaternary time, so that they are not closely related to rocks of the same age across the fault to the northeast. In the segment in the central and southern Coast Ranges, Paleocene and Eocene deposits overlap against the crystalline basement of the Salinian block, and include more continental slope and ocean floor deposits than to the northeast. They lie in places on Upper Cretaceous rocks, but in many other places they overstep directly onto the crystalline basement. The deposits include sequences 10,000 to as much as 20,000 feet (3,000-6,000 m) thick of sandy flysch or turbidite that formed on deep-sea fans at the foot of the continental slope.

The flysch sequences include the Eocene Butano Sandstone of the Santa Cruz Mountains and even thicker flysch in the southern Santa Lucia Mountains, the La Panza Mountains, and the Sierra Madre, which extend from Paleocene to upper Eocene. The latter form the largest outcrop area of lower Tertiary rocks in the coastal belt of California (Tx, Te). They are contiguous to, but in fault contact with, a more varied Paleocene and Eocene sequence in the Santa Ynez Range to the south. In the eastern Santa Ynez Range, the main part of the sequence is the thick Paleocene and Eocene Juncal Formation of arkosic sandstone, shale, and mudstone. Farther west the sequence forms the Anita Shale, Matilija Sandstone, Cozy Dell Shale, and Coldwater Sandstone. The thin lenticular orbitoidal Sierra Blanca Limestone is at the base in many places, and is the only conspicuous carbonate in the Tertiary of the California coastal belt. The Eocene marine strata in this area are succeeded by the red continental Sespe Formation (Toc), mainly Oligocene but including late Eocene at the base, which expresses a major regression of the sea.

South of the Los Angeles Basin, Paleocene and Eocene deposits fringe the western sides of the Santa Ana Mountains and Peninsular Ranges past the Mexican border into Baja California; the strata are tilted westward but are not greatly deformed. In the Santa Ana Mountains, a 4,000-foot (1,200-m) sequence consists of the Paleocene Silverado Formation and the Eocene Santiago Formation, both shallow-water deposits with nonmarine interbeds. To the south in the Peninsular Range, the sequence thins to 1,600 feet (490 m). Here, the upper part, or Poway Group, contains the distinctive "Poway-type" clasts, which are well-rounded gravels of hard, resistant rocks, especially porphyritic rhyolite tuff, whose source area has been much debated but was in some undetermined terrane to the east.

Near the San Andreas fault in the segment from the San Gabriel Mountains southeastward, slivers of marine Paleocene and Eocene rocks occur which were originally parts of extensive formations, now broken and displaced by fault movements. They include the Paleocene San Francisquito Formation of the Valyermo area and Cajon Pass, and the Eocene Maniobra Formations of the Orocopia Mountains northeast of the Salton Sea.

OREGON AND WASHINGTON [1]

Marine lower Tertiary rocks reappear north of the Klamath Mountain barrier of Mesozoic rocks in the coastal belt of Oregon and Washington. In northwestern Oregon, Eocene rocks form a nearly continuous belt of outcrop 40 or 50 miles (100–130 km) wide in the Oregon Coast Ranges west of the Willamette Valley, with only minor cover of younger Tertiary. North of a downwarp along the Columbia River, they reappear in smaller outcrops in the Coast Ranges of southwestern Washington. Farther north, Eocene rocks form a wide band of outcrop around the eastern and northern edges of the Olympic Mountains. Except in the Olympic area, the rocks are only broadly folded.

The lower Tertiary rocks of Oregon and Washington, like those of California, are continental margin deposits, and marine fossils at various levels indicate correlations with the California sequence. Fossils in the lower beds in Oregon indicate correlation with the Capay and Domengine Stages of the lower Eocene of California; the Paleocene is seemingly unrepresented. Nevertheless, the Oregon and Washington Eocene is of markedly different facies, containing large volcanic components that are lacking in California.

The Eocene overlaps the Mesozoic of the Klamath Mountains on the south and that of Vancouver Island on the north, but otherwise its base is not exposed. Except at the margins, much of it probably accumulated on oceanic crust off the edge of the continent. The total thickness of the Eocene here is 10,000 to 20,000 feet (3,000–6,000 m) or more. Because of the associated sedimentation and volcanism, the oceanic basement, and other features, much of the

[1]For general summaries see Snavely and Wagner (1963, 1964).

Eocene of the region can be considered eugeosynclinal; on the Geologic Map, however, only the part of the sequence in which these features occur in exaggerated degree is so indicated.

Along the margins of the depositional trough are shallow-water deposits, passing inland into coal measures, especially east of the Puget Trough on the flanks of the Cascade Range in Washington, and more locally at the north edge of the Klamath Mountains in Oregon. These pass westward into the deep-water marine deposits in the main area of the trough.

Beginning in the earliest Eocene and continuing locally to the end of the Eocene, basaltic volcanics (Teb) were erupted from a series of centers along the axis of the trough. The volcanic material is estimated to have a volume of 60,000 cubic miles (250,000 km^3), the largest of any volcanic unit in the Pacific Northwest. The volcanic bodies are known from south to north as the Umpqua, Siletz River, and Tillamook Volcanics in Oregon, and the Crescent and Metchosin Volcanics in Washington. Thick masses of pillow lavas alternate or interfinger marginally with water-laid fragmental basaltic debris, and at times the volcanic buildup was great enough that parts of the centers emerged as islands.

The earlier volcanics are succeeded in the south by the middle Eocene Tyee Formation, a thick-bedded, graded turbidite of arkosic sandstone and siltstone. Paleocurrent data indicate that it was derived from the pre-Tertiary crystalline basement rocks of the Klamath Mountains to the south. Farther north, the equivalent of the Tyee is gray, tuffaceous siltstone and water-laid pyroclastics.

Upper Eocene rocks are somewhat more restricted than the earlier Eocene, and in many places lie unconformably on them. Alkalic basalt was erupted locally and passes laterally into gray, thin-bedded to massive tuffaceous siltstone and mudstone, called by such names as Nestucca and Yamhill Formations in Oregon. At this time, nonmarine coal measures and other deposits spread farther into the trough.

A tectonic situation different from the rest of the Oregon and Washington Eocene prevailed in the Olympic Peninsula of northwestern Washington. Here, the Eocene encircles the peninsula on the north and east, facing outward toward younger Tertiary formations, and consists of the Crescent Formation of basaltic volcanics 20,000 feet (6,000 m) thick and associated sedimentary units, all of which stand vertically and are in thrust contact with the sheared, partly metamorphosed eugeosynclinal rocks of the core of the Olympic Mountains (Tee, Toee, Tmoe) (Tabor, 1972, p. 1805-1807).

Following the Eocene, there was a widespread withdrawal of the sea so that the succeeding Oligocene occupies much smaller areas within the Coast Range belt.

CONTINENTAL DEPOSITS

The Paleocene and Eocene continental deposits occur in many areas of the interior of the western United States; none are preserved farther east and were probably never laid down there. The largest areas of these deposits are those in the northern Great Plains and Rocky Mountains, which accumulated in basins between and east of mountains that had been newly raised during the Laramide orogenies of late Mesozoic and early Tertiary time. Smaller, more widely separated patches of deposits are preserved in various outlying areas west of the Rocky Mountains from the Canadian to the Mexican borders and were probably never much more extensive than they now are.

The continental deposits have yielded many remains of plants and vertebrates, especially in the Great Plains and Rocky Mountains, from which a system of stages has been constructed that is independent of but parallel to the marine stages of the east and west coasts (Wood and others, 1941). The Paleocene has been divided into the Puercan, Dragonian, Torrejonian, Tiffanian, and Clarkforkian Stages, and the Eocene into the Wasatchian, Bridgerian, Uintan, and Duchesnian Stages. All the stages are based on formations at localities within the Rocky Mountain region, but they have been extended far beyond the original formations into rocks of different facies and settings.

GREAT PLAINS AND ROCKY MOUNTAINS[5]

Paleocene and Eocene continental deposits are extensive in the northern Great Plains and the intermontane basins of the Rocky Mountains. They are closely related to the Laramide orogeny of Late Cretaceous and early Tertiary time, which created the basins, and the intervening uplifted ranges which supplied much of the sediment source. The orogeny also permanently expelled the seas from this part of the continent (with the minor exception of the Cannonball Formation, noted below), so that the deposits were laid down on piedmont slopes or flood plains, in swamps, and lakes. In some of the deeper basins, the deposits attain thicknesses of 10,000 feet (3,000 m) or more. Unconformities at various levels in the sequence, especially along the edges of the basins, attest to the progress of the

[5]For summaries, see Robinson (1972) and McDonald (1972).

orogeny, but the rocks of the basins themselves were little disturbed, and lie nearly horizontal over wide areas.

The unconformities are local, and the sequence in other places is conformable—from the latest Cretaceous into the Paleocene and from the Paleocene into the Eocene—so that there has been much controversy as to age assignments, notably as to the Cretaceous-Tertiary boundary (the so-called "Laramie question"). Many of the deposits are similar from one age to the next, but there was a gradual change in the deposits with time, reflecting different sediment sources, climatic conditions, and other factors; there were also changes in the faunas and floras, reflecting both changes in environment and evolutionary development. Despite the orogeny, the region remained at low altitude through the Paleocene and Eocene; even the mountain areas were not lofty but were worn down by erosion nearly as rapidly as they were raised. A notable change in depositional patterns, probably related to tectonic movements, occurs between the Paleocene and Eocene. The Paleocene forms deposits in nearly all the basins, whereas the Eocene is thick and extensive only in the intermontane basins. In the Great Plains east of the Rocky Mountains the Paleocene spreads out over great areas; the Eocene, if present, is confined to small remnant patches.

PALEOCENE DEPOSITS (Txc)

Both the latest Cretaceous (Laramie, Hell Creek, and Lance Formations) and the Paleocene deposits are somber-gray, lignitic sands and clays that accumulated in swamps in a humid, semitropical environment. Near the mountains, granitic detritus appears in the sequence. Much futile effort was once expended in a search for unconformities in the basin deposits that presumably would mark the Cretaceous-Tertiary boundary, but the deposits are actually conformable, or nearly so. Nevertheless, the highest Cretaceous deposits contain *Triceratops* and others of the last of the dinosaurs, whereas the succeeding Paleocene contains only archaic mammals. However, part of the Laramie flora is of Tertiary aspect, so much adjustment has had to be made to reconcile the plant and animal evidence; this dilemma has now apparently been resolved.

The term *Fort Union Formation* (or Group) has virtually become the generic term for the Paleocene deposits of North and South Dakota, Montana, and Wyoming; farther south other names are used. The Fort Union was named by Meek and Hayden in 1862, during the early days of geological exploration of the northwest, for the now-defunct Fort Union at the mouth of the Yellowstone River near the present town of Buford, North Dakota. In the Williston basin of North Dakota and in many other places, it is as much as 6,000 feet (1,800 m) thick. Because of its uniform character it has not been divided in many places, but elsewhere various components have been recognized and named, such as the Tullock Lake, Lebo, and Tongue River Members (or Formations). Volcanic detritus is rare in the Fort Union; westward in the Crazy Mountains basin of south-central Montana, however, the Fort Union passes into the Livingston Formation, a mass of andesitic tuff that includes highest Cretaceous below.

Along the east edge of the outcrop area, in North Dakota and northern South Dakota, the *Cannonball Formation* (Tx) interfingers westward into the lower part of the Fort Union Formation. It consists of shallow-water marine shales—the last marine deposits of the continental interior, probably formed during a brief incursion from the Arctic. It is named for the Cannonball River in North Dakota, along which its characteristic "cannonball" concretions are prominent. The formation contains oyster banks and about 150 species of mollusks and foraminifers, the latter resembling those of the Midway Group of the Gulf Coast.

The Paleocene deposits are preserved in two smaller areas along the front of the Rocky Mountains farther south, in the Denver and Raton basins of Colorado and New Mexico. In both areas they overlie beds of Laramie age (uK4) and are more or less gradational with them. The Dawson Arkose in the Denver basin is composed of granitic detritus from the adjacent Front Range and intergrades laterally with the finer-grained Denver Formation. In the Raton basin the fine-grained coal-bearing Raton Formation similarly intergrades northward with the coarser Poison Canyon Formation which contains volcanic detritus. At Spanish Peaks at the north end of the basin, it is followed by the small remnant of the Huerfano Formation of Eocene age.

A more complex set of Paleocene deposits occurs much farther west, in north-central Utah southwest of the Uinta basin whose original basinal form is now much disrupted by the block-faulting in the High Plateaus of Utah (Spieker, 1946). Below is the variegated shale, sandstone, and conglomerate of the North Horn Formation which bridges the Cretaceous-Paleocene boundary and contains Cretaceous dinosaurs in its lower part and Paleocene mammals in its upper part. It is followed by the lacustrine Flagstaff Limestone, whose white ledges form a prominent and persistent capping of the High Plateaus. The Flagstaff contains fresh-water mollusks. Variegated clays and marls at the south end of the plateau that have traditionally been called Wasatch Formation are probably of Flagstaff age and are so represented on the Geologic Map (Txc). The lake in which the Flagstaff accumulated varied in shape and size with time, but late in the epoch probably covered most of central Utah although only fragments are now preserved. The Flagstaff is succeeded by the Colton Formation which is considered to be the local representative of the Wasatch Formation, of Eocene age, on the basis of scanty molluscan remains.

It would have been interesting to have differentiated the Flagstaff lacustrine deposits in the same manner as the Eocene (Green River) lacustrine deposits on the Geologic Map, but the areal pattern is too complex for such representation, and they are therefore grouped with the North Horn Formation as Paleocene continental deposits (Txc).

In the San Juan basin to the southeast, in northwestern New Mexico and southwestern Colorado, Paleocene continental deposits about 2,000 feet (600 m) thick lie between the highest Cretaceous (uK4) and the Eocene (Tec) in the center of the basins. In the southern part they comprise the thin, sandy and conglomeratic Ojo Alamo Formation and the thicker, finer-grained Nacimiento Formation. These units are replaced along the north side of the basin by the much coarser Animas Formation (merged with the Upper Cretaceous on the Geologic Map), which contains large quantities of andesitic debris derived from the early eruptions in the San Juan Mountains to the north. The Nacimiento and Animas include the Puerco and Torrejon Formations and "Tiffany beds" of former usage, each of which contains a significant Paleocene mammalian fauna that has served as the basis for the Puercan, Torrejonian, and Tiffanian Stages of the continental Tertiary time scale.

EOCENE DEPOSITS (Tec)

Eocene continental deposits succeed the Paleocene in all the intermontane basins of the Rocky Mountains, and attain sizeable volumes. They are as much as 14,000 feet (4,250 m) thick in the Uinta basin on the south flank of the Uinta Mountains, and exceed 5,000 feet (1,500 m) in many of the other basins. By contrast, Eocene deposits are lacking or inconsequential east of the mountains, where only small remnants of the Golden Valley Formation are recorded above the Fort Union Formation in North Dakota; the Huerfano Formation occupies a small area at the north end of the Raton basin in Colorado.

Eocene deposits record a marked change in conditions from those of the Paleocene—from somber-gray lignitic Paleocene deposits laid down in a moist swampy environment, to red-banded Eocene clastics formed in a drier climate on piedmont slopes and flood plains. Forests gave place to open savannas and grasslands, and the mammalian community changed from forest-dwelling animals to browsing herbivores. At the same time, evolutionary changes resulted in the extinction of the archaic Paleocene mammals and the substitution of mammals of more modern aspect. Primitive horses appeared, and higher up in the sequence (and continuing into the Oligocene) the titanotheres, whose gigantic bones aroused the interest of the first geological explorers, and later became the field of collectors and paleontologists such as Marsh and Cope.

In southwestern Wyoming, northwestern Colorado, and northeastern Utah, terrestrial piedmont and flood-plain sedimentation was interrupted during the middle Eocene by lacustrine conditions whose deposits (the Green River Formation) are differentiated from the rest on the Geologic Map (Tel) and are discussed separately below.

Although the Eocene deposits formed in a tectonic environment, the region remained at an altitude as low as that of the Paleocene; the successive uplifts never attained the height of lofty mountains. The similarity of mammalian faunas from one basin to the next indicates that there were no topographic hindrances to free migration, and in places the original deposits seem to have been confluent between basins, the connections having been removed by subsequent erosion.

The *Wasatch Formation* (Tec) at the base of the Eocene was named by Hayden in 1868 for outcrops in Echo Canyon on the line of the Union Pacific Railroad on the east side of the Wasatch Mountains in northeastern Utah, where its red conglomeratic sandstones are prominent. The type Wasatch was subsequently divided into the Knight, Fowkes, and Almy Formations, but this subdivision now appears to be invalid. The Fowkes is a younger Tertiary tuffaceous deposit accidentally infaulted in the sequence. The lower red sandstones in Echo Canyon, which are unconformable below the Knight, are actually Cretaceous (Echo Canyon Formation); elsewhere, beds mapped as Almy are indistinguishable from the Knight, and the latter is the only true representative of the original Wasatch.

The name Wasatch has been widely extended from the type area to other parts of Utah, Wyoming, Colorado, and New Mexico, but the lithologic Wasatch varies considerably in scope and age from place to place, so that stratigraphic precisionists prefer to substitute local names in the different areas. Nevertheless, it has become virtually a generic term for the early Eocene continental deposits of the region, and it is retained here in this sense. Its faunas are the basis for the Wasatchian Stage of the continental Tertiary time scale. The only exception to the general application of the name Wasatch is in the Wind River basin, where the name Wind River Formation has traditionally been used. The name is of about the same vintage as the name Wasatch, and applies to about the same strata, although it apparently includes some younger beds.

Marginally, the Wasatch is a red, coarse, bouldery piedmont deposit (as at the type locality) that in many places oversteps the Paleocene and Cretaceous to lie on older rocks in the cores of the ranges. Farther out in the basins it is a red-banded sandy clay and sandstone that was probably deposited by streams on flood-plains.

In northeastern Utah, southwestern Wyoming, and northeastern Colorado, the Green River lake beds are overlain by higher Eocene continental deposits (shown as Tec on the Geologic Map, like the Wasatch). They include the Bridger of the Green River basin and the Uinta of the Uinta basin, the latter apparently somewhat younger than the former. The Bridger and Uinta much resemble the Wasatch Formation below but red colors are rarer, and some beds are chocolate brown. Minor lenses of lacustrine deposits occur, and the Bridger contains much fine-grained tuff and other volcanic detritus.

The Duchesne River Formation overlies the Uinta Formation along the southern flank of the Uinta Mountains and has been variously classed as of Eocene or of Oligocene age. On the Geologic Map it is shown as Oligocene (Toc), and it is described below under that series.

In the San Juan basin of northwestern New Mexico, the Eocene of the central part was formerly termed Wasatch Formation, but it has been renamed San Juan Formation. It is about 1,500 feet (450 m) thick and is divisible into various intertonguing members of different lithologies. In the central part are units of shale and fine-grained sandstone, some red, some gray or varicolored, and around the edges are coarse conglomeratic units that were spread as fans into the basin.

EOCENE LACUSTRINE DEPOSITS (Tel)

Middle Eocene lacustrine deposits, known collectively as the Green River Formation, cover an area of about 30,000 square miles (78,000 km^2) in southwestern Wyoming, northwestern Colorado, and northeastern Utah, and have a thickness of 3,000–5,000 feet (900–1,500 m). An outlying lacustrine deposit, the Tatman Formation, occurs in the Bighorn basin to the north, where it overlies the local representative of the Wasatch Formation (= Willwood Formation).

The Green River Formation has been extensively investigated because of its economic potential—its deposits of oil shale and of trona (a form of sodium carbonate)—but much of its broader interpretation and philosophical rationalization is the work of Wilmot H. Bradley (1964 and earlier reports), who has devoted a large part of his scientific career to the subject.

The Green River Formation is preserved in the Green River and Washakie basins in Wyoming, the Piceance basin in Colorado, and the Uinta basin in Utah. It accumulated in Lake Gosiute and Lake Uinta that lay north and south of the Uinta Mountains axis, and which were partly confluent around its eastern end. From time to time, the Rock Springs uplift in southwestern Wyoming formed an island between the Green River and Washakie basins.

The Green River Formation characteristically forms light-colored, thin-bedded outcrops that contrast unmistakably with the adjacent Eocene terrestrial deposits. Much of it is varved, and on the basis of its annual layers it is estimated that the lakes endured for about 6,500,000 years. In detail, its deposits exhibit a great variety of facies, depending on their distance from shore, fluctuations in depth of water and salinity, and of the extent of the lakes throughout time. During much of their life, the lakes had exterior outlets to the north and south, but in the middle of the epoch, in Wyoming at least, the lake shrank, the outlet disappeared, and the waters became highly saline, causing deposition of the beds of trona and other evaporites.

The oil shale (an organic-rich marlstone), one of the characteristic components of the Green River, is especially concentrated in the Parachute Creek Member in the Piceance basin of northwestern Colorado. Other facies include light gray, brown, or buff dolomitic marlstone and shale; dolomitic marlstone thickly studded with salt-crystal molds; oolitic limestone and bedded algal deposits; limy sandstone and sandy marlstone; and beds of volcanic ash that become increasingly abundant upward. Marginally, sandy deposits interfinger with the finer-grained deposits. The formation contains fossil fishes, plants, pelecypods, gastropods, and fly larvae. Bird, mammal, and reptile bones occur in the shore facies.

Because of fluctuations of the lake, the Green River deposits intertongue extensively with the terrestrial Wasatch deposits, especially in Wyoming, where a succession of tongues of Green River and Wasatch have been mapped and named.

OUTLYING AREAS

NEW MEXICO AND WEST TEXAS

South of the Raton and San Juan basins of northern New Mexico, small, widely separated patches of Paleocene and Eocene continental deposits are preserved which are probably remnants of units that were originally more extensive but are now so dismembered that the outlines of their basins are no longer discernible. The basins were probably never as extensive, nor the deposits as thick as those in the Rocky Mountains to the north.

At the north end of the Sandia Mountains northeast of Albuquerque is the Galisteo Formation, about 3,000 feet (900 m) thick, which lies unconformably on the Cretaceous and consists of variegated sand and clay, in part tuffaceous, with some beds of fresh-water limestone. Vertebrate bones at various levels indicate Wasatchian and younger Eocene ages.

West of the Rio Grande farther south, the Baca Formation fringes the north edge of the Datil volcanic field for about 100 miles (160 km), lying unconformably on the Cretaceous to the north and passing southward beneath the younger Tertiary volcanics. It is about 700 feet (210 m) thick and consists of a coarse basal conglomerate followed by red and white sandstone and clay. Indications of age are scanty, but the formation is presumed to be Eocene.

At the north end of the Caballo Mountains just east of the Rio Grande the McRae Formation, about 3,000 feet (900 m) thick, overlies the Upper Cretaceous Mesaverde Formation (Kelley and Silver, 1952, p. 115–120). It consists of a basal conglomerate containing many volcanic clasts that is overlain by maroon shales with some interbedded sandstone layers. Dinosaur bones have been collected in the lower part, and if not reworked, indicate a Cretaceous age for this part. Higher beds contain little but equivocal fossil plants. The formation appears to be older than those just described, and on the Geologic Map it is assigned to the Paleocene (Txc).

The Cub Mountain Formation in the Sierra Blanca area 80 miles (130 km) to the east is similar and probably correlative. It lies unconformably on the surrounding Cretaceous and is followed unconformably by the early Tertiary volcanics that form the heights of the Sierra Blanca peaks.

Much farther south, in the Big Bend region of west Texas and east of the Chisos Mountains, Upper Cretaceous continental deposits are overlain by continental deposits of Paleocene and Eocene ages (Maxwell and others, 1967, p. 98–107). The Black Peaks Formation, an alternation of sand and clay with "cannonball" concretions, is about 800 feet (250 m) thick and contains Paleocene mammals of Torrejonian and Tiffanian ages. It is followed by the very similar Hannold Hill Formation about 500 feet (150 m) thick that contains mammals of Wasatchian age. As both formations crop out in a very small area, they are shown together as Paleocene (Txc) on the Geologic Map.

ARIZONA

To the west in Arizona a dozen or more still smaller areas classed as Eocene continental deposits (Tec) are widely despersed in the Basin and Range province. For the most part they are the units designated as TKs on the State Map (1969). They are tilted and faulted, reddish-brown to gray conglomerate, sandstone, shale, and thin limestone with thicknesses of several thousand feet, which lie unconformably on the Mesozoic and older rocks and lie beneath the main body of Tertiary volcanics and associated sediments. Aside from these structural relations, there is little specific evidence as to their ages, although the deposits in the Artillery Mountains in the western part of the State contain palm roots of possible Eocene age.

One of the more interesting of these units is the Pantano Formation of the Tucson area, 6,500 feet (2,000 m) thick, of sandstone, mudstone, and granite-boulder fanglomerate (Finnell, 1970). Unlike the younger Tertiary continental deposits of the surrounding area, the Pantano has been steeply upended, strongly deformed, and thrust over the gneisses of the Rincon and Catalina Mountains. Like the other continental deposits of southern Arizona, there is little evidence for its precise age; on the Geologic Map it is classed as Eocene (Tec), but radiometric determinations on interbedded rhyolites and andesites yield ages of 25 to 36 m.y., which indicates a range in age between early Oligocene and early Miocene.

NEVADA AND CALIFORNIA

In southern Nevada east of Las Vegas, the Horse Spring Formation consists of more than 1,000 feet (300 m) of yellowish siltstone, whitish limestone, and an upper unit of coarser clastic deposits (Longwell and others, 1965, p. 45–48). The formation is conformable on the Cretaceous and older rocks of the district, and is unconformable beneath the late Tertiary Muddy Creek Formation. Fossils are scanty and the age of the Horse Spring is uncertain. It contains a few plants, pelecypods, and gastropods of possible Eocene age, but radiometric determinations at one locality suggest a Miocene age. On the Geologic Map it is indicated as Eocene (Tec).

The lower Tertiary continental deposits west of the Sierra Nevada in California have already been noted (p. 7). East of the Sierra Nevada the only one recorded is the Goler Formation of the El Paso Mountains, a short distance north of the Barlock fault (Nilsen and Clarke, 1975, p. 24). It is about 6,500 feet (2,000 m) thick, lies unconformably on an igneous and metamorphic basement, and is overlain by Pliocene continental deposits. It consists of a lower conglomerate and breccia unit, overlain by arkosic sandstone and red mudstone. Fossil plants in the Goler have been ascribed an Eocene age, but its vertebrates are probably Paleocene. It is indicated as Paleocene (Txc) on the Geologic Map.

WESTERN MONTANA

Within the mountains of western Montana are a few early Tertiary continental deposits.

In the Flathead Valley west of the Lewis and Livingston Ranges, or frontal ridges of the Belt terrane at the Canadian border is the Kishenehn Formation, an early Tertiary deposit much obscured by Pleistocene glacial deposits (Ross, 1959, p. 67-72; described as "older alluvium"). It consists of well-bedded, well-indurated, fine-grained sand, silt, and clay, with some interbedded lignite. From place to place it contains plant remains, mollusks, and fish. The bulk of the material seems to be late Eocene, but some collections may be of Miocene or other Tertiary ages. It is represented as Eocene (Tec) on the Geologic Map.

Much farther south, in the Lima region of southwestern Montana, is the Beaverhead Conglomerate (Scholten and others, 1955, p. 368-369), which occupies the low ground in front of many of the ranges, and is overthrust in places by the Mesozoic and Paleozoic rocks; in other places it lies unconformably on them. It is as much as 9,000 feet (2,700 m) thick and consists of coarse red conglomerate, with interbedded sandstone and some fresh-water limestone. It is evidently a synorogenic deposit, formed during the deformation of this part of the Rocky Mountains, and is probably Paleocene (Txc), although fossil control is sparse. At one locality north of Lima it is overlain unconformably by deposits that contain late Eocene mammals (Sage Creek Formation). About 40 miles (65 km) to the east of the Lima region, the Sphinx Conglomerate forms a small outlier on the summit of the Madison Range and is probably correlative with the Beaverhead.

WASHINGTON

In central Washington, on the east side of the Cascade Range in the latitude of Seattle, is a complex array of lower Tertiary continental deposits and associated volcanics that were elucidated early in the century by the work of Smith (1904), and Smith and Calkins (1906); they were later reviewed by Foster (1960).

At the base is the Swauk Formation (Txc) more than 4,000 feet (1,200 m) thick, a nonvolcanic fluviatile deposit composed largely of arkose, in part conglomeratic, with some interbedded shale, that lies unconformably on pre-Tertiary metamorphic and plutonic rocks. It contains fossil plants of Paleocene age. In the mountains to the west are smaller areas of the Guye Formation, once thought to be younger, but now known from paleobotanical evidence to be correlative.

The Swauk is overlain unconformably southward by the Teneaway Basalt and the local Silver Pass Volcanics 1,000-5,000 feet (300-1,500 m) thick (lTv), which are followed conformably by another continental deposit, the Roslyn Arkose, whose leaves and rare vertebrate remains are middle or upper Eocene. The Guye Formation to the west is also followed by Eocene continental deposits and volcanics, such as the Naches Formation which contains fossil leaves.

The lower Tertiary rocks of central Washington are overlain unconformably by the lower part of the great volcanic sequences of the Cascade Range and Columbia Plateau—on the west the Miocene Keechelus Andesite (uTa) and on the east the Yakima Basalt at the base of the Miocene Columbia River Group (Tmv).

Farther north, on the west side of the Cascade Range, is the Chuckanut Formation (Txc). It is lithically much like the Swauk, of similar origin, similarly unconformably on the pre-Tertiary rocks, and with fossil plants of about the same age, but it attains thicknesses of 15,000 feet (4,500 m) or more. Various small to large outliers of Paleocene continental deposits occur in the Cascade Range between the Swauk and Chuckanut, which suggest that the two formations were once connected.

EUGEOSYNCLINAL DEPOSITS[6]

The only Tertiary rocks shown as eugeosynclinal on the Geologic Map are those in the core of the Olympic Mountains of northwestern Washington, whose sparse fossils indicate an early Eocene to Miocene age. However, a considerable part of the

[6]Abstracted from manuscripts in preparation by W. M. Cady and R. W. Tabor.

Eocene rocks of the coastal belt of Oregon and Washington also have many eugeosynclinal qualifications, being marine turbidites and interbedded submarine basaltic volcanics that accumulated on an oceanic crust.

The peripheral rocks of the Olympic Mountains surround the core on the north, east, and southeast and are a thick, steeply-dipping, outward-facing sequence that ranges in age from Eocene to Miocene. The Eocene part, mainly the Crescent Formation, resembles that farther south in the coastal belt, already described (p. 8).

The core rocks are thrust-faulted against the peripheral rocks. These faults, including the Hurricane Ridge fault on the north, now dip steeply, but probably originally dipped eastward at a much lower angle; they and other concentric faults within the core form the boundaries of crustal slabs that were subducted eastward from the ocean floor beneath the continent and its marginal deposits. Westward into the core, each slab consists of rocks somewhat younger than those in the slab to the east; hence, the Geologic Map distinguishes units from east to west as of Eocene age (Tee), Oligocene and Eocene age (Toee), and Miocene and Oligocene age (Tmoe).

The core rocks are marine shales, turbidites, and minor basalts. To the east they are penetratively sheared, and metamorphosed to phyllite and semischist of prehnite-pumpellyite and low-rank greenschist facies (Tabor, 1972) (on the Geologic Map they are shown with a metamorphic overprint, although elsewhere on the map this overprint is reserved for rocks of amphibolite grade or higher). Beds and folds are commonly sheared out and the sandstones form boudins. To the west, the rocks are still highly folded and faulted but are less penetratively sheared and the only metamorphic minerals are zeolites.

Sparse microfossils and megafossils indicate that the core rocks to the east are Eocene (a few collections may be Paleocene, but nothing older is known). Westward in the core more numerous fossils indicate late Eocene and Oligocene ages, and near the coast early to middle Miocene.

Rocks in the core include pillow basalt, basaltic breccia and tuff, tuffaceous argillite, and associated limestone. The basaltic rocks are especially abundant in the eastern, or Eocene block, where they form pods and lenses in sheared rock but were probably originally autochthonous. The rarer lenses of basaltic rock in the blocks farther west might be allochthonous, as the youngest foraminifers so far identified in the associated limestones are all Eocene.

The sediments in individual outcrops indicate consistent, outward-facing sequences, but no general stratigraphic sequence is determinable; most of the rock is "broken-formation," and passes in places into melange.

OLIGOCENE SERIES

The Oligocene Series, which formed during about 11 million years of mid-Tertiary time, corresponds to the Tongrian, Rupelian, and Chattian Stages of the European marine sequence and is divided into the Chadronian, Orwellian, and Whitneyan Stages of the American continental sequence. The Oligocene is only meagerly represented on the Geologic Map of the United States (fig. 2)—among the marine deposits of the Gulf Coastal Plain and the Pacific northwest (To), among the continental deposits of the northern Great Plains and Rocky Mountains (Toc), and in smaller areas elsewhere. Some other deposits may be of Oligocene age but are mapped with the series above or below on the Geologic Map. Oligocene volcanic rocks in the western United States are grouped with others of the lower Tertiary (lTv).

MARINE STRATIFIED ROCKS

GULF COASTAL PLAIN

Strata of Oligocene age are shown on the Geologic Map of the United States as a narrow band of outcrop in the eastern Gulf Coastal Plain extending from Mississippi into Georgia, and less continuously eastward into South Carolina and westward into Louisiana. They emerge again in northern and central Florida on the flanks of the Ocala uplift. No Oligocene is known in the Atlantic Coastal Plain north of South Carolina, at least at the surface. No Oligocene is mapped in the western Gulf Coastal Plain in Texas, although the non-marine Frio Clay of the southern part of the State may be of this age; it was grouped with the Miocene on the Geologic Map on the advice of D. H. Eargle (oral commun., 1971).

The Oligocene of the outcrops in the Gulf Coastal Plain is only a few hundred feet thick, but it thickens to many thousands of feet downdip in subsurface where a complex stratigraphy has been worked out. The outcrops in the eastern half of the Gulf Coastal Plain are dominantly calcareous, with many limestone beds and formations, which are interbedded with marl and lesser sand and clay, giving rise to many thin stratigraphic units.

The most prominent part of the Oligocene is the middle, or Vicksburg Group, named in 1848 for exposures near Vicksburg, Mississippi, at the west end of the main outcrop belt. The Vicksburg is divided in Mississippi and Alabama into the Mint Spring Marl, Marianna Limestone, and Byram

Limestone, as well as various minor units or members. The Marianna and Byram Limestones form the main part of the Oligocene in Florida.

In the type region the Vicksburg is underlain by the Forest Hill Sand and Red Bluff Clay, which lie on the Jackson Group; and it is overlain by the Chickasawhay Marl and its equivalent, the Flint River Formation, which in Florida passes into the Suwannee Limestone.

To the west, across the Mississippi River in Louisiana, only equivalents of the Vicksburg persist in the outcrops, which are here dark shale with some sandy and lignitic layers. They are overlapped near the west edge of the State by the Miocene Catahoula Formation and do not come to the surface in Texas—unless the Frio Clay in the far southwest is of Oligocene age.

PACIFIC COASTAL AREA

California

The Oligocene of California is represented by the Lincoln and Blakeley Stages of marine megafossil zonation, and the greater part of the Refugian Stage of microfossils. However, there is much uncertainty as to the correlation of beds assigned to the Oligocene in California with the type Oligocene in Europe, so that there is controversy as to the exact limits of the true Oligocene. In addition, Oligocene was a time of widespread emergence in the coastal area of California, so that the supposed Oligocene formations are very locally distributed and rather thin. On the Geologic Map, the Oligocene is thus not shown for the most part, its strata being merged with the underlying Eocene or overlying Miocene.

The largest area of Oligocene shown on the map is the Sespe Formation, a nonmarine unit about 5,000 feet (1,500 m) thick that is intercalated in the marine sequence in the western part of the Transverse Ranges; from place to place the Sespe extends from the upper Eocene into the lower Miocene. It is a red clastic deposit largely of granitic debris that contains vertebrate bones at several levels. At the western end of the Santa Ynez Mountains it grades into marine beds (Alegria and Gaviota Formations).

Farther north, marine formations of Oligocene age (not represented on the Geologic Map) include parts of the San Lorenzo Formation of the Santa Cruz Mountains and the Kreyenhagen Shale of the western part of the San Joaquin Valley.

Oregon and Washington

In the northern coastal belt of Oregon and Washington, as in California, the Oligocene is thinner and more restricted than the Eocene, but its outcrops are large enough to be represented on the Geologic Map. Much of the anticlinorium of the Oregon Coast Ranges was emergent, and the Oligocene deposits occur along its west and east edges and around its north end.

Vigorous pyroclastic volcanism in the Cascade Range to the east caused the Oligocene marine deposits to be dominantly tuffaceous; they pass eastward into volcanic-rich continental deposits along the edge of the Cascade Range, which lack the coal measures of the preceding Eocene. The Oligocene deposits include the Yaquina Formation of the Oregon coast, composed of cross-bedded arkosic and tuffaceous sandstone, and the Lincoln Formation of the Washington coast, consisting of massive tuffaceous siltstone and fine-grained sandstone. East of the Coast Range uplift in Oregon is the richly fossiliferous Eugene Formation. North of the Olympic Mountains along the Strait of Juan de Fuca, more than 10,000 feet (3,000 m) of Oligocene silts and clays were deposited. As this area was farther removed from the volcanic activity to the east, these deposits contain much less tuffaceous material than the other Oligocene units.

CONTINENTAL DEPOSITS

Continental deposits of Oligocene age are widely distributed in the northern part of the interior region of the Western United States, but individual outcrop areas are mostly small and widely dispersed, the largest being in the Great Plains and eastern part of the Rocky Mountains. In many places, especially toward the west, the Oligocene continental deposits are intermingled with contemporaneous volcanic rocks, which are grouped with the other lower Tertiary volcanics (lTv) and are described separately later.

GREAT PLAINS AND ROCKY MOUNTAINS

The *White River Formation* (or Group) has become the generic name for most of the Oligocene deposits in the Great Plains of South Dakota, Nebraska, and Colorado, and westward into the Rocky Mountains of Wyoming. The formation was named by Meek and Hayden in 1858 for the White River in southwestern South Dakota southeast of the Black Hills, along which it is spectacularly exposed in the Big Badlands. To the south, the White River reappears from beneath the Miocene and Pliocene deposits in the valleys of the North and South Platte Rivers, where it extends from the front of the Rocky Mountains in Wyoming and Colorado, eastward into Nebraska. Outliers of the White River to the west in Wyoming are mostly in intermontane basins, but some occur high up in the mountains, indicating the great original extent of this broad sheet of deposits.

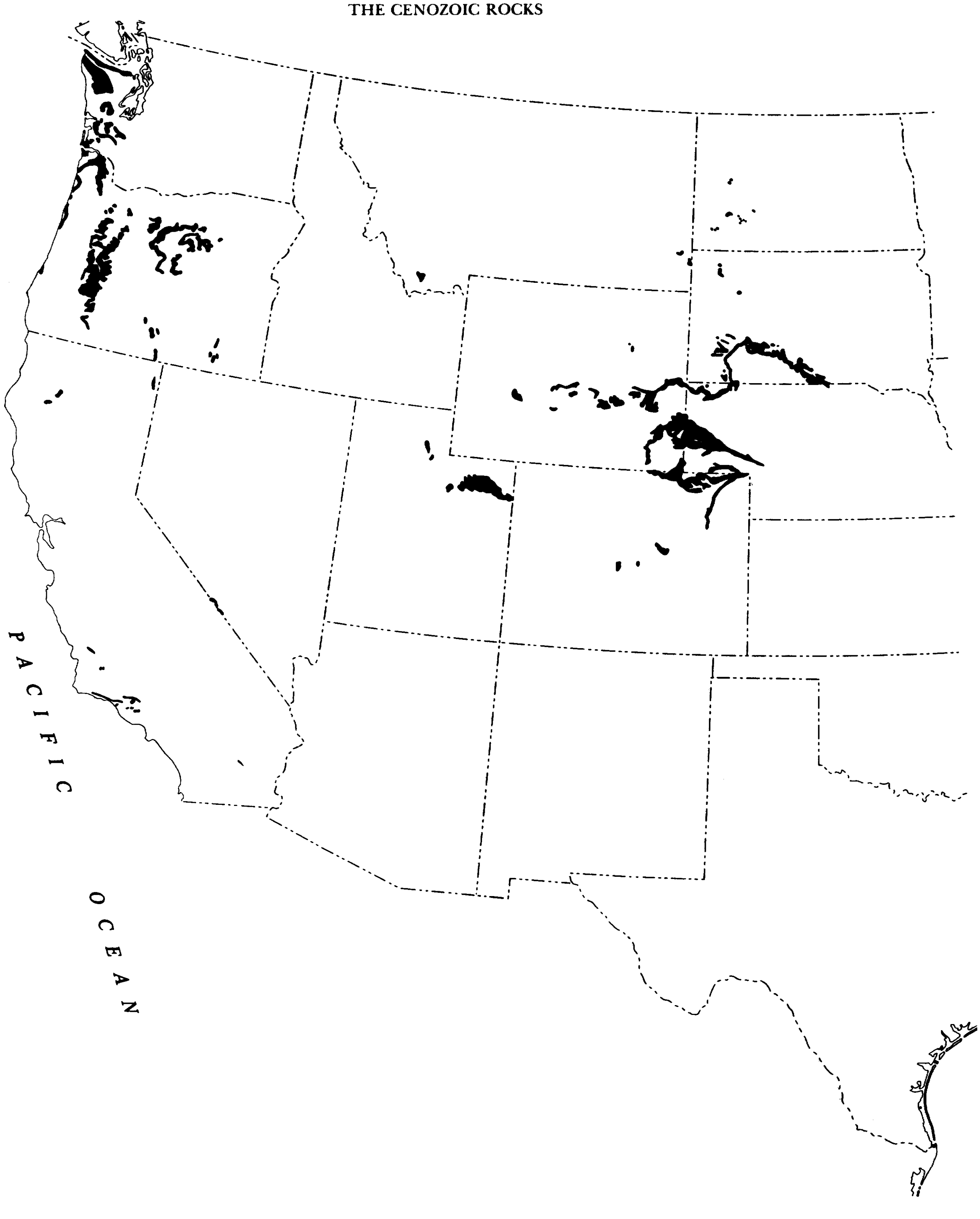

FIGURE 2.—Map of the United States showing surface distribution of Oligocene stratified rocks as represented on the Geologic Map of the United States (units To, Toc, Toee).

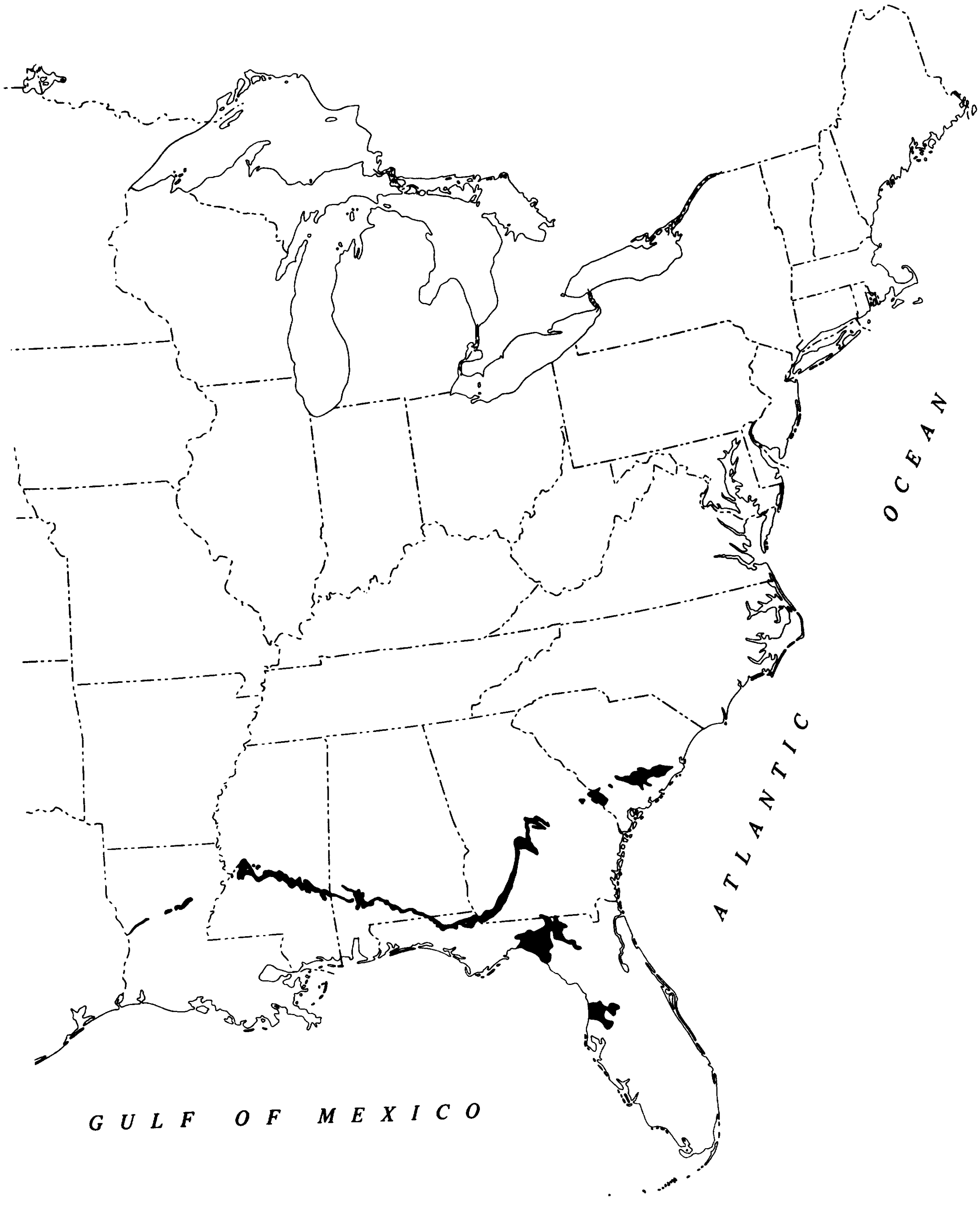

FIGURE 2.—Continued.

In its type area in the Great Plains, the White River is 600 to 700 feet (180–210 m) thick, but elsewhere it is mostly thinner. In the Great Plains it is divided into the Chadron Formation of clay, sandy clay, and river-channel sandstone, and the overlying thicker, finer-grained Brule Clay. A somewhat older Oligocene deposit forms Slim Buttes northwest of the main area in South Dakota and is locally present beneath the Chadron elsewhere. Both the Chadron and Brule abound in vertebrate bones, notably the gigantic titanotheres (Osborn, 1929, p. 103–112).

The White River Formation is a terrestrial deposit that was spread across a broad plain sloping gently eastward from the Rocky Mountains and has been little deformed since. (An early idea that it was a subaqueous deposit laid down in a vast lake has long since been discredited.) It includes massive, lenticular river-channel sandstones, surrounded by more extensive finer-grained flood-plain or overflow deposits, and occasional deposits that were laid down in local ponds and marshes. Volcanic ash forms occasional layers. The river channels can be traced for considerable distances, and extend eastward and southeastward from the mountains. Their mineral content can be matched with their respective sources—the Black Hills, the Laramie Range, and the Front Range (Clark, 1975, p. 99-104). Probably the rivers coalesced eastward into streams draining south into the Gulf of Mexico. The excess of deposition in the region can be attributed to a general change from the moist climate of Eocene time to one of increasing aridity.

The vertebrate faunas of the White River reflect these varied environments. The fine-grained flood-plain deposits contain chiefly plains and grassland animals, whereas the river-channel deposits contain chiefly forest and fluviatile animals. The lagoon and swamp deposits contain fish, alligators, and aquatic plants.

South of the White River area, in the Great Plains of Colorado, the Castle Rock Conglomerate forms a small outlier in the center of the Denver basin south of Denver. It is essentially an extension of the White River deposits and contains many of the same vertebrate bones. It is underlain by a rhyolite ash-flow tuff lying unconformably on the Paleocene deposits that has been dated radiometrically at 34.8 m.y. and is probably an extension of the Thirtymile volcanic field in the Front Range to the southwest (Steven, 1975, p. 83).

Within the southern Front Range itself are the Florissant Lake Beds, famed for their plant and insect remains, but with very few vertebrates (MacGinitie, 1953). Underlying tuff beds have a radiometric age of 35 to 36 m.y., and the lake beds cannot be greatly younger. The lake beds accumulated in a shallow basin on a surface carved in late Eocene time and dammed by the eruptions of the Thirtymile volcanic field to the west. Their floras indicate that the lake beds formed in a warm, subhumid climate at an altitude of about 3,000 feet (1,000 m), as compared with their present altitude of 9,000 feet (2,750 m).

On the south flank of the Uinta Mountains is the Duchesne River formation (Toc). It lies conformably on the Eocene Uinta Formation, but it is a coarser deposit that represents a new cycle of sedimentation, and it overlaps northward on the pre-Tertiary rocks. Opinions differ as to whether the formation is of Eocene or Oligocene age; the Duchesnian Stage of the continental Tertiary is conventionally placed in the Eocene, but at least the uppermost members (La Point and Star Flat) are certainly Oligocene (Clark, 1975, p. 110). It has yielded a K/Ar age of 39.3 m.y.

OUTLYING AREAS

Oregon

In north-central Oregon the John Day Formation flanks the Blue Mountains uplift on the northwest, where it lies unconformably on the Eocene Clarno Formation (lTv), and is overlain unconformably by the basalts of the Columbia River Group (Tmv). Both the Clarno and John Day are of volcanic origin, but the John Day is more dominantly sedimentary, hence is shown as continental deposits (Toc) on the Geologic Map. The John Day is about 2,000 feet (600 m) thick and is composed largely of tuffaceous sediments—water-laid tuffaceous siltstone and rhyolitic air-fall tuff and ash-flow tuff. It has been famous since the turn of the century for its mammalian remains, which are assigned to the Whitneyan and Arikareean Stages of the continental Tertiary (upper Oligocene and lower Miocene).

Farther west in Oregon, in the western part of the Cascade Range, are the lower Tertiary andesites of the Little Butte Volcanic Series (lTa) (Peck and others, 1964, p. 11-26). In some segments of its outcrops, nearly three-quarters of the series consists of poorly bedded andesitic tuff and breccia; andesitic lapilli tuff, welded tuff, and breccia; stratified tuff and tuffaceous sandstone and conglomerate. These volcaniclastic components of the Little Butte Series are shown separately on the Geologic Map as continental deposits (Toc). Fossil plants indicate that they are of middle Oligocene to lower Miocene age.

In the Basin and Range part of southern Oregon, the lowest unit exposed in Steens Mountain and other block-faulted ranges is the Cedarville Formation (Toc), typified by exposures in the Warner Range of northeastern California, where as much as 7,500 feet (1,200 m) is exposed (Russell, 1928, p. 402-416). It consists of andesitic tuffs, agglomerates, and mudflow deposits, with minor lava. The lower beds contain a middle Oligocene flora, but the upper part extends into the Miocene. The Cedarville is unconformable beneath the main Miocene and Pliocene volcanic sequences in the ranges.

California

In the southwestern Klamath Mountains of northern California are several small areas of the Weaverville Formation (Toc) (Irwin, 1966, p. 29-30), which is a deposit of sandstone, shale, conglomerate, tuff, and lignite as much as 2,000 feet (600 m) thick, that contains fossil plants of Oligocene age. The Weaverville lies unconformably on the pre-Tertiary basement rocks of the Klamath Mountains and was probably deposited in local, partly down-faulted depressions.

In eastern California, in the Grapevine Mountains east of Death Valley, the Paleozoic rocks are overlain by the Titus Canyon Formation (Toc), about 3,000 feet (900 m) thick, composed of sandstone, in part tuffaceous, conglomerate, mudstone, and algal limestone, that contains lower Oligocene (Chadronian) mammals (Stock and Bode, 1935). Farther south in the Death Valley region the Oligocene is volcanic (Artists Drive Formation, lTv).

In the Orocopia Mountains of southeastern California, east of the Salton Sea and the San Andreas fault, marine Eocene rocks (Maniobra Formation, Te) are overlain by an unnamed unit of nonmarine conglomerate, sandstone, and mudstone (Toc) of probable Oligocene and possible lower Miocene age.

MIOCENE SERIES

The Miocene Series, whose rocks formed during about 14 million years of mid-Tertiary time, corresponds to the Aquitanian, Burdigalian, Helvetian, Tortonian, Samartian, and Pentian Stages of the European marine sequence. In North America, as in the Eocene and Oligocene, the marine sequence in California, and the continental sequence in the interior region, are divided into stages of local application. Next to the Eocene and Paleocene, the Miocene is the most extensively exposed Tertiary series in the United States (fig. 3). Marine deposits (Tm) occur in the Atlantic and Gulf Coastal Plains and the Pacific coastal areas of California and farther north. Continental deposits (Tmc) are extensive in the northern Great Plains and Rocky Mountains and in smaller areas in the interior region farther west. Miocene volcanic rocks (Tmv, Tmf) are widely distributed in the western interior, where they interfinger in many places with the continental deposits; they are treated under a later heading.

MARINE STRATIFIED ROCKS

GULF COASTAL PLAIN[7]

The Miocene formations are exposed in a narrow to wide band of outcrop in the shoreward part of the Coastal Plain that extends continuously from the Rio Grande in Texas to South Carolina, except for a 20-mile (32-km) alluvium-covered gap along the Mississippi River. Miocene rocks are also extensive throughout the Florida peninsula. On the outcrop the Miocene is about 2,000 feet (600 m) thick, and most of it from Alabama westward is brackish-water or continental deposits. It changes to marine in subsurface downdip where it contains a sequence of widely traceable foraminiferal zones. It thickens dramatically, especially across growth faults downthrown toward the coast, so that near the Texas and Louisiana coast it attains 48,000 feet (14,500 m) (Crouch, 1959, p. 1285-1286).

Terminology of the Miocene deposits has been much confused by a host of stratigraphic names that have been used in different senses by successive authors (Murray, 1961, p. 407-412). Actually, in surface outcrops at least, the gross subdivisions are fairly clear.

At the base in the western half of the Coastal Plain is the Catahoula Sandstone, named for Catahoula Parish, Louisiana, and recognized from Alabama to Texas. In Texas it is generally 200-300 feet (60-90 m) thick and is formed of clay and sandstone. The clay is bentonitic and noncalcareous, and the sandstone fine- to medium-grained, cross-bedded and tuffaceous. In south Texas the formation thickens to 1,000 feet (300 m) and is more coarsely volcanic; this part was called the Gueydan Formation by Bailey (1926) and is now distinguished as the Catahoula Tuff. Its volcanic clasts include boulders, pebbles, and chunks of lava, porphyry, and pumice. Many of these can be specifically matched with contemporaneous volcanic formations in the trans-Pecos mountains and upstream along the Rio Grande, but some show so little water-rounding that they may have come from now-concealed volcanic centers in the Coastal Plain itself. The Catahoula in Texas contains a few brackish-water mollusks and more abundant plants, including palms that must have grown in tropical coastal swamps.

The Catahoula Sandstone contains workable deposits of fuller's earth in east Texas (King, 1940, p. 179-182) and important deposits of uranium in south Texas (Eargle and others, 1975, p. 773-777).

In south Texas the Catahoula is underlain by the Frio Clay 150 feet (45 m) thick, of lacustrine origin. Its age is uncertain and it might be Oligocene, although it is included with the Miocene on the Geologic Map. Northward, the Catahoula oversteps the Frio and lies unconformably on the Eocene.

In Texas, from the Brazos River southwestward, the Catahoula is followed unconformably by the

[7]Compiled from many sources; few modern summaries are available, but earlier summaries by Plummer (1932, p. 710-749) and Cooke (1945, p. 190-195) are still useful.

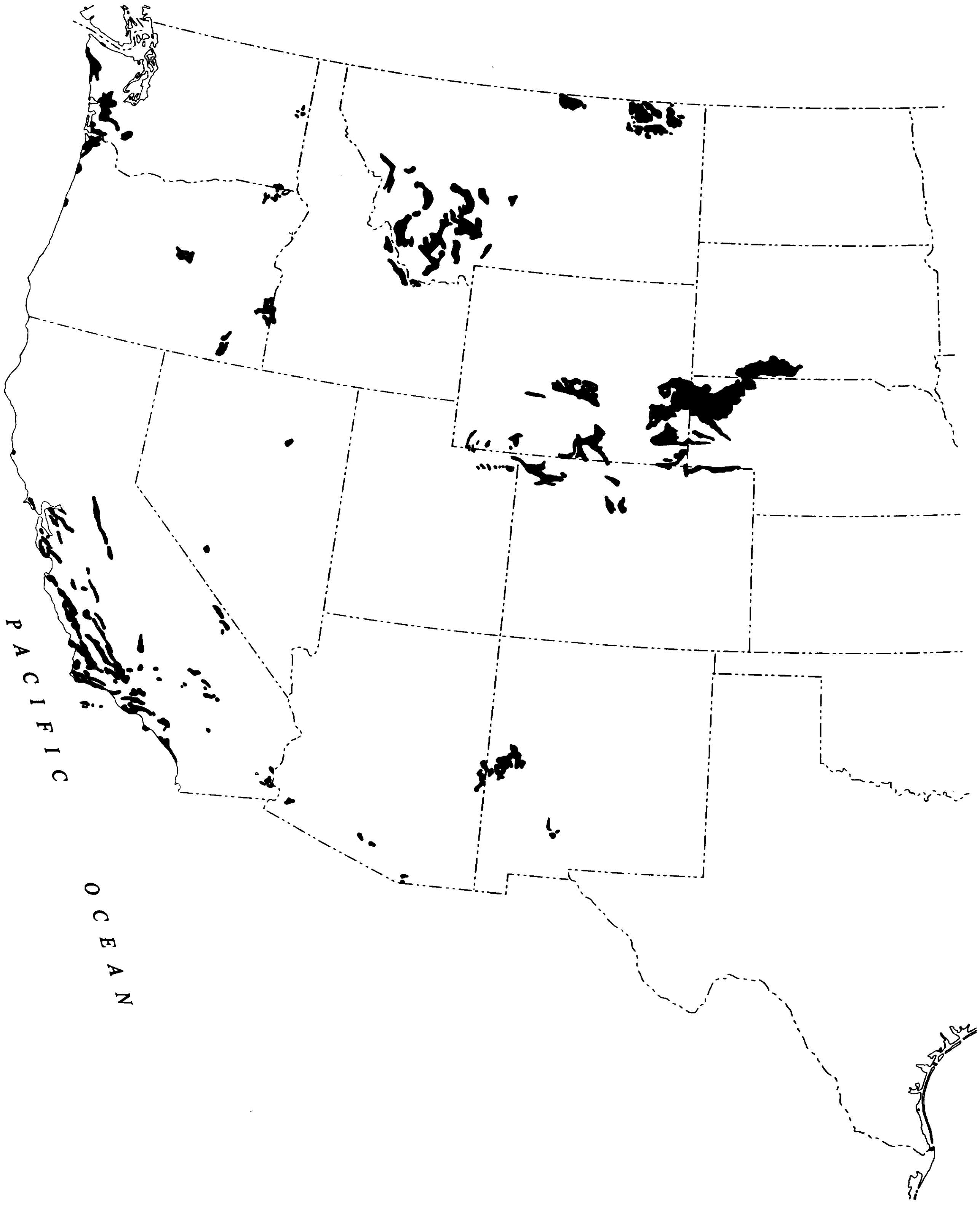

FIGURE 3.—Map of the United States showing surface distribution of Miocene stratified rocks as represented on the Geologic Map of the United States (Tm, Tmc, Tmoe).

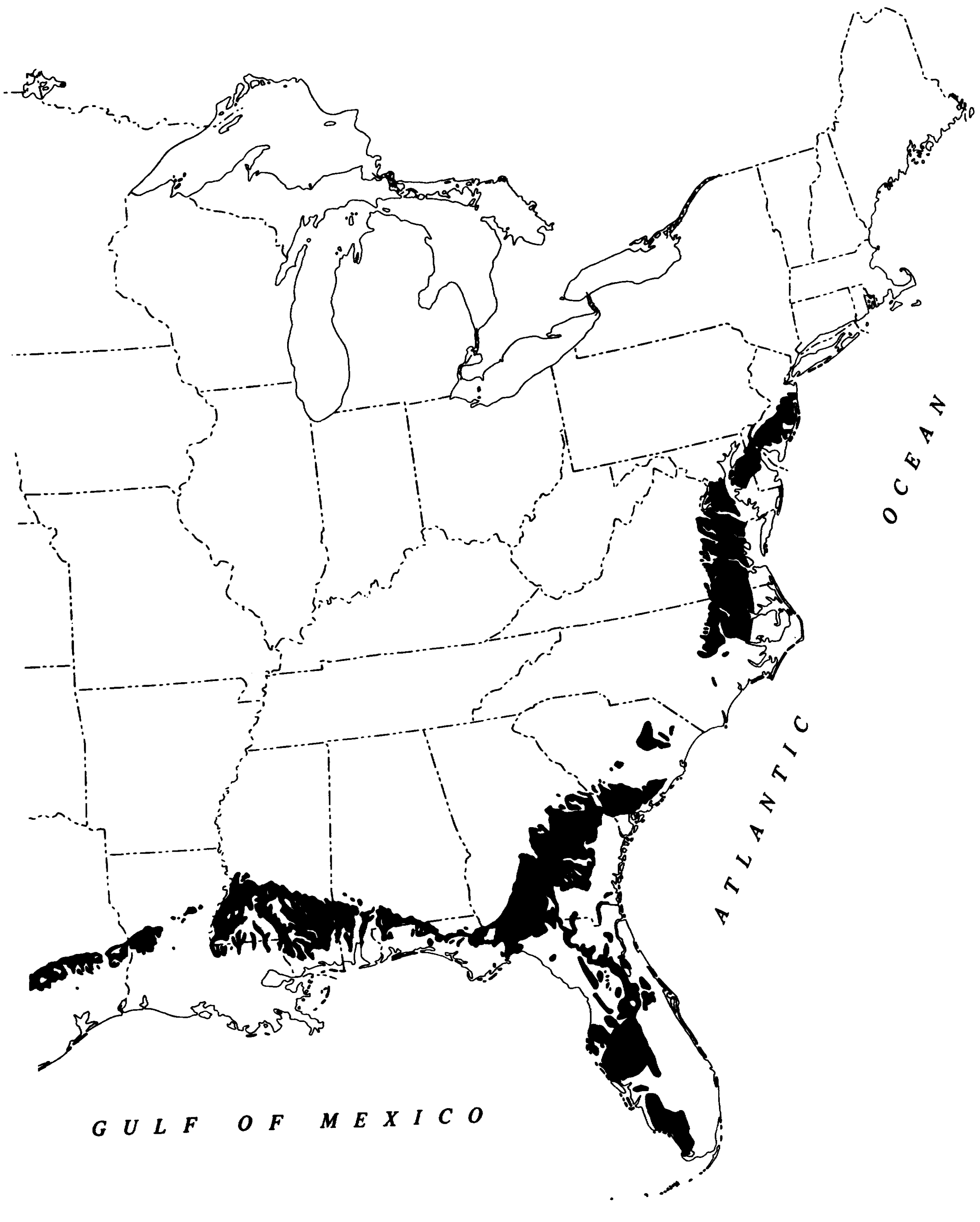

FIGURE 3.—Continued.

Oakville Sandstone 200-500 feet (60-150 m) thick, a coarser deposit formed during a new cycle of sedimentation. Drainage during its deposition was now from the northwest, from Cretaceous outcrops near and beyond the Balcones Escarpment, and the gravels contain notable quantities of reworked Cretaceous marine shells (as much as 5 percent of the volume). The Oakville Sandstone also contains abundant bones of horses, camels, mastodons, and rhinoceros that are of Arikareean and Hemingfordian (middle Miocene) age. No marine fossils are known on the outcrop, but occur in subsurface a short distance downdip.

The Oakville is followed conformably by the Fleming Formation (= Lagarto Clay) and merges eastward with its lower part. The Fleming is 1,200 feet (360 m) thick and is similar to the Oakville but finer grained. It contains brackish-water mollusks and mammalian bones of Barstovian (latest Miocene) age.

The nonmarine facies of the Miocene continues in surface outcrops eastward across Louisiana and Mississippi into Alabama. The lower sandy beds are everywhere termed Catahoula, but the upper beds are divided into the Hattiesburg and Pascagoula Clays, each about 400 feet (120 m) thick. The Pascagoula contains a few layers with marine fossils.

In the eastern part of the Gulf Coastal Plain, the exposed Miocene passes into a marine, calcareous, highly fossiliferous facies of about the same thickness as the nonmarine deposits farther west. At the base in Florida and Georgia is the Tampa Limestone, more variable and less pure than the Oligocene and Eocene limestones beneath it; it is approximately equivalent to the Catahoula Sandstone farther west. It is followed by the Alum Bluff Group, comprising the Chipola and Shoal River Formations and the local Oak Grove Sand. The Chipola includes coarse siliceous sand and limestone, and the Shoal River is chiefly sand and clay. The Alum Bluff passes northeastward into the Hawthorne Formation, which is extensive in Georgia and extends as far as South Carolina. The Hawthorne consists of gray phosphatic sand with lenses of fuller's earth that are mined commercially in many places. Besides its invertebrate shells, it contains mammalian bones of Hemingfordian age.

ATLANTIC COASTAL PLAIN[8]

North of a gap in North Carolina where Cretaceous formations extend nearly to the coast on the Cape Fear arch, Miocene deposits are extensive in the Atlantic Coastal Plain as far as New Jersey. The Miocene units are, in fact, the most extensive of the Tertiary deposits of this part of the Coastal Plain, and in places overstep the older Tertiary and Cretaceous so that they extend onto the pre-Mesozoic crystalline rocks of the Piedmont province.

The Miocene consists of a number of thin shaly and sandy formations, all marine and very fossiliferous, all separated by unconformities. In Maryland, Delaware, and northern Virginia, it consists of the middle Miocene Calvert, Choptank, and St. Mary's Formation, overlain toward the south by the Yorktown Formation, traditionally classed as upper Miocene, which is the most extensive unit in southern Virginia and North Carolina. In New Jersey, the middle Miocene is represented by the Kirkwood and Cohansey Formations, and no equivalents of the Yorktown are present.

The Calvert Formation is prominently exposed in the Calvert Bluffs on the west shore of Chesapeake Bay in Maryland, where it consists of diatomaceous clay with a shell bed in the middle that is a mass of pelecypods and gastropods; the shells weather free and strew the modern beaches of the bay. The overlying Choptank is more sandy but is also very fossiliferous. The St. Mary's is clay, sandy clay, and sand.

The Yorktown at the top is typically exposed in the bluffs of the York River at Yorktown, Virginia, and consists of coquina, marly sand and clay, and glauconitic sand. Recent paleontological work indicates that it and the Duplin Marl (its extension into South Carolina) are lower Pliocene in age, rather than upper Miocene in terms of European standard sections (J. E. Hazel, written commun. April, 1975). Moreover, glauconite in the Yorktown has yielded a Pliocene K/Ar age of 4.4 m.y. The Yorktown is the only upper Tertiary unit exposed south of the James River in Virginia and beyond through North Carolina; hence, all the Miocene shown on the Geologic Map in this segment of the Atlantic Coastal Plain should be transferred to the Pliocene.

PACIFIC COASTAL AREA

CALIFORNIA[9]

The Miocene of the coastal area in California has the most complex display of rocks and formations, and the thickest sequences in surface exposures (9,000 feet, 2,700 m, or more) of any Miocene rocks in the United States. It occurs in numerous small outcrops in the Coast Ranges south of San Francisco bay, eastward across the San Joaquin Valley, southward across the western part of the Transverse Ranges, around the Los Angeles Basin, and along the western flank of the Peninsular Ranges nearly to the Mexican border. Narrow fault-bounded slices of what were originally extensive Miocene formations extend eastward along the north side of

[8]For summary, see Spangler and Peterson (1950, p. 61, 75-79).

[9]Earlier summaries are given by Reed (1933, p. 163-226) and Reed and Hollister (1936, p. 32-46); more recent data appears in publications by Kleinpell (1938) and Bramlette (1946).

the Transverse Ranges. Continental deposits of Miocene age are widespread in southeastern California, especially in the Mojave Desert region.

A large body of knowledge regarding the California Miocene has accumulated, partly as a result of academic research, partly from petroleum exploration, and can only be summarized briefly here. The California Miocene has long been divided on the basis of marine megafossils into the Vaqueros, Temblor, Briones, Cierbo, and Neroly Stages, but these are rather vague and not entirely satisfactory, as they are based on rock-stratigraphic units mainly in the Central Coast Ranges. Later, it was divided on the basis of foraminifers into the Zemorrian, Saucesian, Relizian, Luisian, Mohnian, and Delmontian Stages (Kleinpell, 1938, p. 103-157). These stages are believed to be more nearly time-stratigraphic units, which cut through the complex array of formations and rock facies, and they have come into wide use.

North of the Transverse Ranges, the San Andreas fault zone extends through the Miocene formations. This segment of the fault has undergone more than 300 miles (480 km) of right-lateral displacement during and since Miocene time, which has resulted in marked offsets of Miocene facies across it, such as the boundary between marine and continental deposits, and the boundary between warm-water and cold-water marine faunas (Addicott, 1968). Clearly, the geography during Miocene time was quite different from that at present, which greatly complicates paleogeographic reconstructions.

Lower Miocene deposits (Zemorrian and Saucesian) include much fairly coarse clastic material, and in various places have been termed the Vaqueros and Temblor Sandstones. The most characteristic rocks of the younger Miocene are diatomite and associated siliceous sediments, whose white, thin-bedded ledges are a characteristic feature of the landscape of the Coast Ranges and other parts of California (Bramlette, 1946). They are known collectively as the Monterey Formation, but they are a facies that varies greatly in scope and age from place to place—in places only middle Miocene, in others both middle and upper Miocene and even basal Pliocene. The siliceous rocks include porcelanite or siliceous mudstone, laminated siliceous shale, and thin-bedded chert and cherty shale. Diatomite, or diatom-rich siliceous rock, occurs mainly in the upper parts of individual sequences; however, the lower siliceous rocks were also probably originally diatomaceous and have been altered by diagenesis. The siliceous rocks intertongue marginally with mudstone, siltstone, and sandstone, which in some areas replace them entirely. The upper Miocene in the Salinas Valley of the central Coast Ranges is again a coarse clastic deposit, the Santa Margarita Formation.

Volcanic rocks (Tmv), mainly andesite and basalt, are a locally significant component of the California Miocene. They occur, for example, at The Pinnacles in the Gabilan Range of central California, and in the western Santa Monica Mountains farther south, where they are more than 5,000 feet (1,500 m) thick. Tuffaceous deposits and bentonite are widely distributed in the middle and upper Miocene. There is a possible, although unproved relation between the volcanic episode and the widespread distribution of siliceous sediments.

The marine Miocene deposits grade eastward and southeastward into continental deposits. The latter occur at the western foot of the Sierra Nevada along the eastern side of the San Joaquin Valley (Mehrten and Zilch Formations), which to the west toward the San Andreas fault in the Bakersfield area change to marine deposits. West of the San Andreas fault in the latitude of Bakersfield, the continental deposits are offset northward, so that the transition into marine deposits occurs near Caliente Mountain. To the south in the Transverse Ranges are the Tick Canyon and Tecuya Formations with Arikareean and Hemingfordian (lower Miocene) mammals and the Mint Canyon Formation with Barstovian (upper Miocene) mammals. There are unsolved discrepancies in age assignments between these fossiliferous continental deposits and the fossiliferous marine deposits with which they intergrade (Durham and others, 1954).

Structural unconformities occur at many places below, above, and within the California Miocene, but individual unconformities are of local extent and are seemingly represented elsewhere by conformable sequences. There were thus no universal times of orogeny and deformation during the epoch. Nevertheless, there seems to have been a general reorganization of depositional regimes in middle Miocene time as a result of tectonic movements; middle and upper Miocene deposits appear to have been more extensive and varied than those of the lower Miocene.

OREGON AND WASHINGTON

In the northwestern coastal area of Oregon and Washington, Miocene marine deposits are much less extensive than in California; most of the Tertiary rocks of the Coast Ranges are Eocene and Oligocene. The Miocene is mostly confined to narrow strips along the coast, although it extends somewhat farther inland in the Grays Harbor area of southwestern Washington.

In the Newport embayment of western Oregon, the lower Miocene is represented by 3,500 feet (1,000 m) of the organic-rich Nye Mudstone, but the most extensive formation along the coast is the middle Miocene Astoria Formation, which consists of about 1,000 feet (300 m) of sandstone and siltstone.

The Astoria is interbedded with basalt flows erupted from local centers and is succeeded along the downwarp near the Columbia River by basalt of the Columbia River Group (Tmv) that flowed from the main eruptive area of flood basalts east of the Cascade Range. Near the coast, the normal terrestrial basalts of the Columbia River pass into accumulations of pillow lava and breccia.

CONTINENTAL DEPOSITS

NORTHERN GREAT PLAINS AND ROCKY MOUNTAINS

In the north-central Great Plains, in the segment centering in western Nebraska and southeastern Wyoming, Miocene continental deposits are part of the great sheet of outwash that was spread on the slope east of the Rocky Mountains from Oligocene through Pliocene time. Much of the Miocene has traditionally been assigned to the Arikaree Group, but an overlying Hemingford Group has been recognized later (Lugn, 1939, p. 1251-1258). These groups are the types of the Arikareean and Hemingfordian Stages of the continental Tertiary, although the Hemingford apparently contains beds of the Barstovian Stage at the top.

The Miocene deposits are 500–1,000 feet (150–200 m) thick in western Nebraska, but wedge out eastward and southward between the underlying and overlying Tertiary. Channeling is characteristic, and each successive formation lies on a channeled surface of the one beneath. For example, the Gering Formation at the base of the Arikaree lies on a deeply channeled surface cut on the Oligocene Brule Clay, and the Marsland Formation at the base of the Hemingford lies with marked erosional unconformity on the Harrison Formation of the Arikaree. Some of the channels, such as those of the Gering Formation, contain coarse sand and gravel, but for the most part the Miocene sediments are fine-grained sands and silts, indicating that during the epoch the Rocky Mountains were not actively shedding material. The upper part of the Sheep Creek Formation at the top of the Hemingford is less channeled than the rest and consists of fine-grained flood-plain material and aeolian silt.

Westward in the Rocky Mountains of Wyoming and Colorado, the Miocene deposits are preserved in separate basins, in some of which they attain thicknesses much greater than those in the Great Plains. The basins approximate the original depositional sites, but during the later Miocene, to judge from the occurrence of scattered outliers, sediments seem to have been spread widely between the basins and across some of the intervening ranges.

One of the most extensive Miocene deposits is the Split Rock Formation, typically developed in the Sweetwater area in the center of Wyoming, where it surrounds and partly buries the Precambrian rocks of the Granite Mountains (Wg) (Love, 1961, p. 5-25). It is about 2,700 feet (830 m) thick, and vertebrate evidence indicates that it includes most of the Arikareean and Hemingford Stages. It consists mainly of fine-grained silty sandstone with some units of coarser porous sandstone. Much of the sediment was derived from the northwest, and some of it is of aeolian origin; the Rocky Mountains were not actively shedding detritus during Split Rock time.

In the vicinity of the eastern Uinta Mountains, 130 miles (210 km) southwest of the Sweetwater area, is the Browns Park Formation. It is typically developed in a graben that splits the crest of the Uinta Mountains at their eastern end, but it extends farther east along the valley of the Yampa River; remnants also occur along the south flank of the Uinta Mountains and along the west flank of the Park Range, indicating that the deposit was originally much more extensive. The Browns Park is about 1,800 feet (550 m) thick, and most of it is white or gray, fine-grained, tuffaceous sandstone of aeolian and fluviatile origin, but at the base is a coarse conglomerate, composed of quartzite of the Uinta Mountain Group (Y). Mammalian remains indicate that the formation is mainly upper Miocene (Hemingfordian and Barstovian); radiometric ages range from 26 m.y. to 9 m.y. (Izett, 1975, p. 186-189).

On the north flank of the Uinta Mountains is the Bishop Conglomerate, which caps a series of high terrace remnants. Its conglomerates resemble those at the base of the Browns Park Formation, with which it is not in contact, which has led to the suggestion that it is of the same age, but present indications are that it is earlier Miocene. To the east, between the Park and Front Ranges, are smaller areas of Miocene continental deposits, the North Park and Troublesome Formations, largely uppermost Miocene.

In the high plains of northwestern Montana, close to the Canadian border and far from the formations just discussed, the Flaxville Gravel forms the cap of remnant plateaus on top of the Paleocene and high Upper Cretaceous rocks. It is a few hundred feet thick and consists of gravel derived from the Rocky Mountains far to the west intermingled with some sand and clay. Rather abundant vertebrates suggest a late Miocene or early Pliocene age; it is shown on the Geologic Map as Miocene (Tmc).

A different set of deposits occurs in the basins within the mountains of southwestern Montana. They were originally termed the "Bozeman lake beds," but most of them are fluviatile rather than lacustrine in origin, and modern work indicates that they are heterogeneous, including deposits of many Tertiary ages, now collectively referred to as the Bozeman Group (Robinson, 1961, p. 1003-1004). Included in the Bozeman Group in some of the basins are Eocene and Oligocene strata that are unconformable beneath the younger Tertiary. The younger Tertiary forms the greater part of the surface areas of the basins, and its vertebrates indicate late Miocene and Pliocene ages; it is shown on the Geologic Map as Miocene (Tmc). The deposits include coarse conglomerate and fanglomerate along the edges of the ranges, and finer-grained sediments farther out. They were laid down in intermontane depressions produced by downwarping and downfaulting during various stages of Tertiary time. The Miocene and Pliocene deposits much resemble those that were laid down in intermontane basins farther south in the western interior that are shown on the Geologic Map as Pliocene and Quaternary (Tpc, Q), but the average age of the deposits in Montana seems to be somewhat greater.

OUTLYING AREAS

NEW MEXICO AND ARIZONA

Continental deposits classed as Miocene are shown in many small areas in western New Mexico and southern Arizona. A few have been dated by fossils or by radiometric means, but most are inferred to be middle Tertiary from their relation to underlying and overlying Tertiary sediments and volcanics. Most of the deposits are within or on the borders of mountain areas, hence are older than the Basin and Range faulting or contemporaneous with its early phases.

In northern New Mexico, west of the Rio Grande Valley, is the Carson Conglomerate, a coarse bouldery deposit composed of clasts of volcanic and Precambrian rocks. It surrounds and half buries the Precambrian rocks of the Petaca area (Xm), and overlaps Mesozoic rocks to the west. It is overlapped in turn on the east by the Pliocene rocks of the Rio Grande Valley. Aside from being obviously middle Tertiary, its exact age is undetermined.

Farther south, at the south end of the Caballo Mountains, are the Palm Park and Thurman Formations (Kelley and Silver, 1952, p. 120-123). The first is a red bouldery deposit with many volcanic clasts, the second a light buff tuffaceous clay. They overlap the Paleozoic rocks of the Caballo Mountains and are overlain by the Pliocene Santa Fe Formation of the Rio Grande Valley. The formations seem to be younger than the Paleocene McRae Formation (Tx) at the north end of the mountains, although not in contact with it, and are probably of middle Tertiary age.

West of the Rio Grande in southwestern New Mexico is the extensive Mogollon-Datil volcanic province, which continues into southeastern Arizona. The volcanic rocks have been called collectively the Datil Formation, but recent work indicates that they include at least three major subdivisions of Oligocene and Miocene ages (Elston and others, 1973, p. 2261-2263). Most of the Datil rocks are lavas, but the New Mexico Geologic Map (1965) represents the northwestern part as clastic rocks of volcanic fragments (Tds) and boulder beds and coarse clastic rocks (Tdc). Their westward extension is shown on the Arizona Geologic Map (1969) as undifferentiated Tertiary sediments (Ts). They are shown on the Geologic Map of the United States as Miocene continental deposits (Tmc), but they may well be Oligocene.

Farther southwest, in the Basin and Range province of southern Arizona, widely separated small areas in the ranges are shown on the Arizona Geologic Map (1969) as Miocene and Miocene(?) sedimentary rocks (Tms). They are shown on the Geologic Map of the United States as Miocene continental deposits (Tmc). They consist of conglomerate, sandstone, siltstone, limestone, tuff, and minor lavas. Some are known to be of Miocene age from fossils or radiometric dating.

WASHINGTON AND OREGON

In the Spokane area of northeastern Washington is the Latah Formation, a lacustrine deposit that accumulated in valleys dammed during the eruption of the basalts of the Columbia River Group. The Latah consists of clay and sand, in part tuffaceous, and beds of diatomite. Rather abundant fossil plants indicate middle and upper Miocene ages. Although the formation is extensive in small areas along the northeast edge of the basalt plateau, only a few of the larger areas can be indicated on the Geologic Map where they are shown as Miocene continental deposits (Tmc).

In the volcanic area of southeastern Oregon, Miocene lavas cover wide areas, and sediments are interbedded with them in many places, some forming areas large enough to be represented on the Geologic Map as Miocene continental deposits (Tmc). They include the Mascall Formation of the western part of the Blue Mountains uplift, which contains Barstovian vertebrates and plants, and the Payette Formation of eastern Oregon and southwestern Idaho, which contains Miocene plants.

CALIFORNIA

Some of the Miocene continental deposits that interfinger with nearby marine deposits in the Coast Ranges and Transverse Ranges have already been noted (p. 25). Miocene continental deposits also extend much farther east in southeastern California, into the Mojave Desert and thence eastward to the Colorado River. As in adjoining southern Arizona, the deposits are preserved in small patches in the ranges where they overlie pre-Tertiary sedimentary and plutonic rocks, and they are intermingled with volcanic rocks of Miocene age (Tmv). Many small areas are shown on the atlas sheets of the Geologic Map of California, where they are indicated as Mc. Not all of them can be represented on the Geologic Map of the United States, and some of them are merged with the associated volcanic rocks.

The Miocene continental deposits of the Mojave Desert have long been referred to as the "Rosamund Series," but this term has been loosely applied to beds with a wide range of ages, and the Miocene part has now been renamed the Tropico Group (Dibblee, 1958, p. 136). In the western part of the desert, it is about 2,800 feet (850 m) thick and is divided into an assortment of sedimentary and volcanic formations, none of which are of more than local extent. The Tropico (= Rosamond) is not very fossiliferous in its type area, but the probably equivalent Barstow Formation farther east contains abundant mammalian remains of upper Miocene age, which are the basis of the Barstovian Stage of the continental Tertiary. The Ricardo Formation, northwest of Barstow across the Garlock fault, has sometimes been compared with the Barstow Formation, but its mammalian fauna is Clarendonian, or early Pliocene.

Along the northern border of the San Gabriel Mountains, at the south edge of the Mojave Desert, are narrow fault wedges of formerly more extensive middle Tertiary continental deposits; pink, massively bedded coarse sandstone and interbedded siltstone. The Punchbowl Formation lies south of the San Andreas fault, and the Cajon Formation 30 miles (90 km) to the east lies north of it. The two formations may be parts of the same deposit, now separated by right-lateral displacement on the fault, but it has been objected that the Punchbowl contains Clarendonian vertebrates and the Cajon Barstovian vertebrates. This argument loses force when it is realized that both units are sparsely fossiliferous and very thick—the Punchbowl 6,000 feet (1,800 m) and the Cajon 8,000 feet (2,400 m). The discrepancy in ages of the known faunas may well be due to the vagaries of collecting.

PLIOCENE SERIES

The Pliocene Series is commonly considered to have formed during the final 10 million years of the Tertiary Period (2-10 m.y. ago) and to correspond to the Plaisancian and Astian Stages of the European marine sequence and to the Clarendonian, Hemphillian, and Blancan Stages of the American continental sequence. However, a considerable body of opinion now favors reducing the length of the Pliocene to 3 million years (2-5 m.y. ago) (Berggren and Van Couvering, 1974) and placing the Clarendonian and part of the Hemphillian continental stages in the upper Miocene. Also, the marine stages that have been proposed in Europe for the upper Miocene and lower Pliocene are suspect as time units; some may be lateral facies of others. There is difference of opinion, besides, as to the Pliocene-Pleistocene boundary. The Pleistocene is commonly assumed to begin with the first glaciation (Nebraskan in North America), but in terms of the marine sequences farther south in Europe, the base is defined as the boundary between the Astian and Calabrian (= Villafranchian) Stages, which appears to be older than the first glaciation, lending support for the concept of a "preglacial Pleistocene" epoch.

Pliocene marine deposits (Tp) are very scantily developed within the United States (fig. 4), due probably to a general emergence of the continent; on the Geologic Map they are shown in the Gulf Coastal Plain and Atlantic Coastal Plain and in the Pacific coastal belt of California. Pliocene continental deposits (Tpc) are much more extensive, especially in the Great Plains and the Cordilleran region of the western United States. In the Cordilleran region there are also many occurrences of Pliocene volcanic rocks (Tpv, Tpf) which are discussed under a later heading.

MARINE STRATIFIED ROCKS

ATLANTIC AND GULF COASTAL PLAINS

The only truly marine Pliocene rocks shown on the Geologic Map are in the southeastern part of the Atlantic Coastal Plain (although, as noted above, the Yorktown Formation and Duplin Marl farther north may also be early Pliocene). Farther west, in the Gulf Coastal Plain, the Pliocene deposits are brackish water or continental, but they are discussed here for convenience.

In Florida the principal Pliocene formation is the Caloosahatchee Marl (Tp) exposed near Lake Okeechobee in the southern part of the peninsula. It consists of sand and beds of molluscan shells, many of which are indistinguishable from modern species (Cooke, 1945, p. 214-227). As the terrain in this part of Florida is low and flat, only a few feet of the formation is exposed at any place, but the total thickness is probably not great. The Caloosahatchee grades laterally into the Buckingham Marl and the Tamiami Formation which, although separately named, are merely facies of the same deposit.

Farther north in Florida, remnants of Pliocene deposits are scattered over the older Tertiary rocks, but are not shown on the Geologic Map. They include the Alachua and Bone Valley Formations, which are estuarine or terrestrial deposits, sometimes filling sinkholes, with a fauna mainly of vertebrates. They are notable for their phosphate, concentrated by weathering from the underlying formations.

Near the coast in eastern South Carolina is the Waccamaw Formation (Tp), which is approximately equivalent to the Caloosahatchee, and like it is a thin fossiliferous layer of sand and shells.

Far to the west, in south Texas, is the Goliad Formation (Tp), which forms a band of outcrop on the downdip side of the Miocene Formations extending from the Rio Grande as far north as the Colorado River (Plummer, 1932, p. 750-760). Although shown as marine on the Geologic Map, it is primarily a brackish water and fluviatile deposit. The Goliad consists of 100-200 feet (30-60 m) of clays and fine to coarse sands, with much gravel in the lower part, cemented in places by caliche. The gravels are mainly chert and quartz pebbles but include bone fragments from the underlying Miocene. It contains a few indigenous mollusks and vertebrate bones, the latter being of Pliocene age and comparable to those of the Ogallala Formation of northwestern Texas. Northeast of the Colorado River the Goliad is overlapped by the younger Willis Sand (= Citronelle).

The Citronelle Formation (Tpc) and its equivalents are the most extensive Pliocene deposits in the Coastal Plain and are shown on the Geologic Map in discontinuous outcrops from central Texas to Georgia, at the outer edge of the Tertiary deposits, and next to the Quaternary deposits along the coast.

The Citronelle was named for a locality in southwestern Alabama (Matson, 1916) to replace the discredited term "Lafayette," which had been used indiscriminately for a wide variety of terrestrial deposits fringing the coastal part of the Coastal Plain Tertiary. In Texas equivalent deposits are termed the Willis Sand. In Louisiana terminology has been confused by the Pleistocene terrace sequence proposed by Fisk (1938, ff), who believed that his oldest and highest terrace surface and deposits, the Williana, were equivalent to the Citronelle, but if the Williana exists in the form envisioned by Fisk, it is probably younger (Doering, 1956, p. 1832-1837).

The Citronelle forms a thin sheet on the uplands along the coastward part of the Tertiary outcrop and extends long distances inland as erosion remnants along the interfluves, truncating the earlier (mainly Miocene) deposits. Its basal surface and its deposits slope coastward at a lower angle than the dip of the underlying strata, but steeper than the nearly undisturbed Pleistocene deposits that border it toward the coast. The Citronelle was laid down after the older Tertiary had been tilted and peneplaned and was tilted in turn prior to the Pleistocene; these tiltings express a regional epeirogenic upwarp of the continental interior late in Tertiary time.

The regional extent of the Citronelle has been reviewed by Doering (1956, 1960), who extends its equivalents northeastward in the the Atlantic Coastal Plain beyond the last outcrops shown on the Geologic Map, in Georgia, across South Carolina, North Carolina, into Virginia. In these States, as farther south, thin deposits overlie the older Tertiary and Cretaceous on the interfluves, but since they are not clearly differentiated on our source maps, they are omitted from the Geologic Map. Across the Potomac, in the Coastal Plain of southern Maryland is the Brandywine Formation, likewise an upland remnant of fluviatile deposits of possible late Pliocene or early Pleistocene age. The Brandywine may be equivalent of the Citronelle, although the great distance and the lack of fossil control renders this correlation speculative at best. The Brandywine is not shown on the Geologic Map (but see King and Beikman, fig. 15).

The Citronelle deposits consist of a basal gravelly sand overlain by sandy clay and clayey sand, laid down by streams that were vigorously eroding the continental interior as a result of the late Tertiary

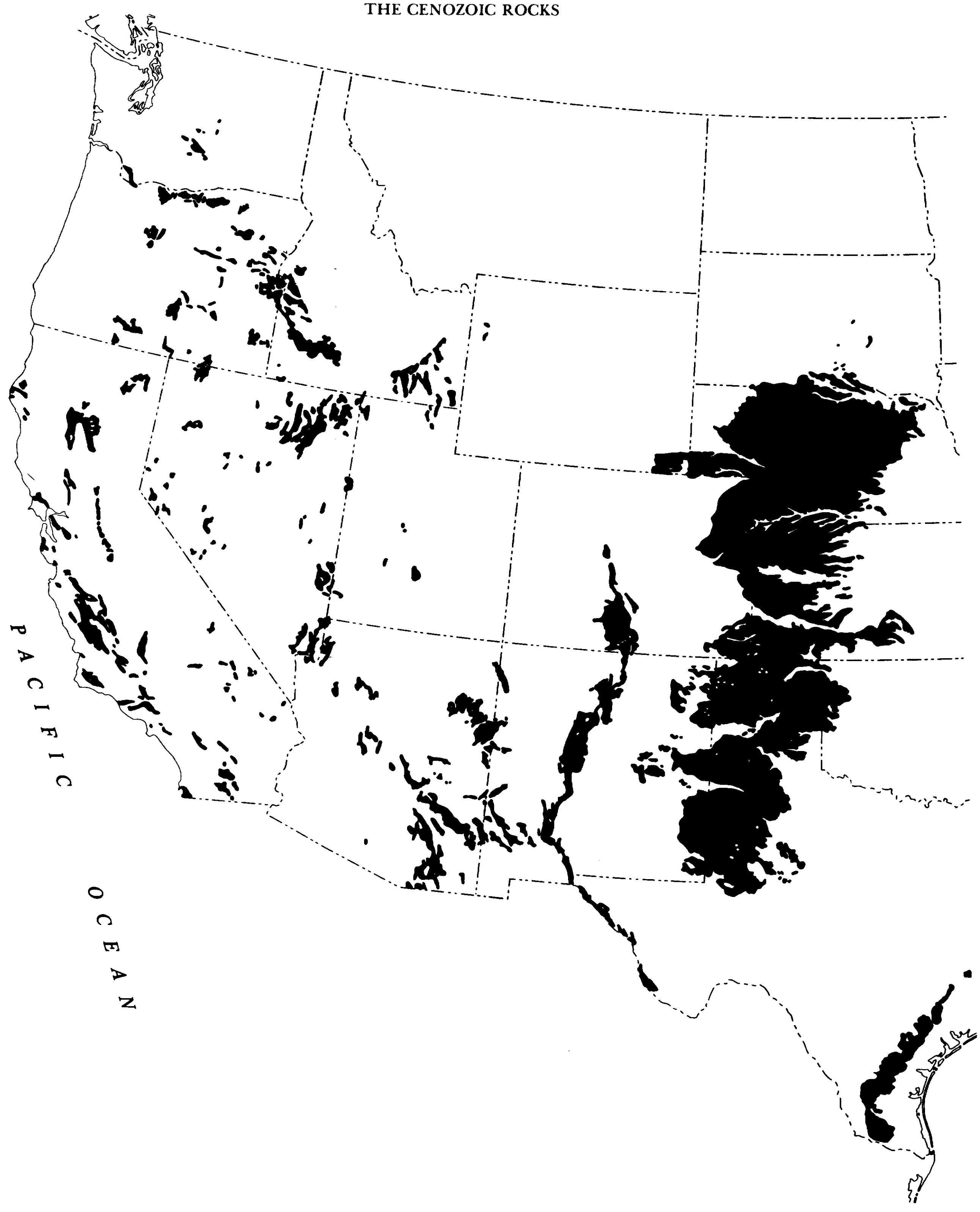

FIGURE 4.—Map of the United States showing surface distribution of Pliocene stratified rocks as represented on the Geologic Map of the United States (units Tp, Tpc).

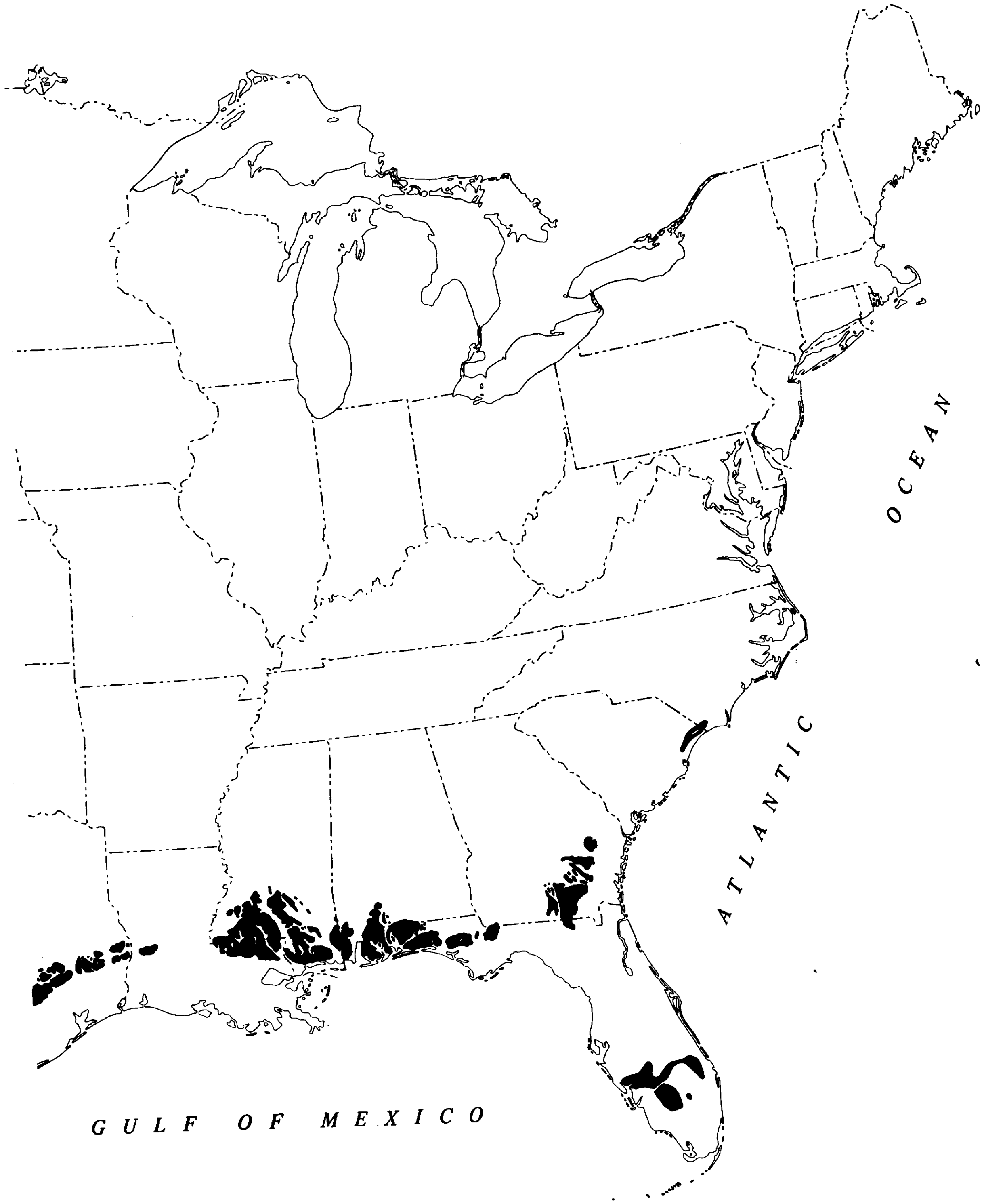

FIGURE 4.—Continued.

epeirogenic uplifts. Toward the coast, some of the deposits accumulated in lagoons, estuaries, and marshes. In the type area in southwestern Alabama, the formation is as much as 300 feet (90 m) thick; elsewhere it is 100-150 feet (30-45 m) thick, but the top is commonly eroded. In the type area, the basal deposits contain fossil plants at one locality, and abundant vertebrate bones at another, both of late Pliocene age (Isphording and Lamb, 1971, p. 776-777). The upper part of the formation may extend into the Pleistocene, and arguments have been presented that it is mainly a "pre-glacial Pleistocene" deposit (a stage not recognized by the U.S. Geological Survey, hence the assignment of the formation to the Pliocene on the Geologic Map).

PACIFIC COASTAL AREA IN CALIFORNIA

In the Pacific coastal area, Pliocene rocks occur only in California, where they are extensive. As shown on the Geologic Map, they are exposed from the north to the south ends of the State, but they are most abundant in the central and southern Coast Ranges and Transverse Ranges, and eastward to the border of the San Joaquin Valley. Many of the deposits are marine (Tp), but continental deposits (Tpc) are more abundant eastward, and upward in the sequence. Pliocene continental deposits also fringe the western foot of the Sierra Nevada along the east edge of the San Joaquin and Sacramento Valleys.

The Pliocene deposits of California are notable for their great thickness, especially in rather local areas. Surface sections of marine Pliocene strata in the Ventura basin exceed 15,000 feet (4,500 m), and similar thicknesses may occur in subsurface in some of the other basins. Continental deposits nearly as thick occur in some of the enclosed basins in the Coast Ranges and elsewhere.

As with the older Tertiary, the Pliocene rocks have been deformed, in places steeply. In some of the best known areas, especially in the Los Angeles and Ventura basins and the south part of the San Joaquin Valley, the sequences are conformable through the Pliocene into the lower Pleistocene, and the two are strongly unconformable with the overlying upper Pleistocene. This has given rise to a widely held belief that the major orogeny in the coastal belt was mid-Pleistocene ("the greatest since the Cretaceous"), but in other areas major unconformities occur within the Pliocene or at its base, so that the supposed mid-Pleistocene orogeny was merely the terminal phase of a long sequence of tectonic instability. During this interval, the ranges between the basins were in process of uplift with little internal deformation.

The marine Pliocene of California is divided into the Jacalitos, Etchegoin, and San Joaquin megafossil stages, and into the Repettian, Venturian, and Wheelerian foraminiferal stages. In addition, the Clarendonian, Hemphillian, and Blancan Stages of the continental Pliocene sequence are frequently referred to.

Pliocene marine deposits are exposed in many areas near the coast of California, but the principal occurrences and greatest thicknesses are in embayments where the ocean extended inland from the present coast—the large Los Angeles basin in the south, and the smaller Ventura and Santa Maria basins farther northwest. In addition, a thick sequence of marine deposits occurs in the southwest part of the San Joaquin Valley farther inland, which was formed in a tongue of the sea somehow connected with the ocean across the site of the southern Coast Ranges (the connection probably now offset from its original position by displacement on the San Andreas fault). Another marine embayment, represented by small outcrops on the west side of the Imperial Valley to the southeast, is unrelated to the rest, and it formed in a former northward extension of the Gulf of California.

In the Los Angeles and Ventura basins, the Pliocene marine strata are divided into the Repetto and Pico Formations. The deposits are mostly sandy silts and sandy clays, some diatomaceous, a little coarser in the Repetto than the Pico. Sandstone and conglomerate are interbedded in the lower part, and interfinger marginally toward the east, where they pass eventually into continental deposits. Foraminiferal studies indicate that in the Ventura basin, and probably also in the Los Angeles basin, the initial Pliocene deposits were laid down in water 4,000-5,000 ft (1,200-1,500 m) deep, and that the water gradually shoaled during the epoch, as a result of filling of the basin with sediments (Natland and Kuenen, 1951, p. 80-85). The basin was filled by deposits brought in by turbidity currents, which show most of the classic turbidite structures. The coarse sandstones were brought in by submarine slumps off adjacent gravelly shores and beaches. Many shallow-water fossils and fragments of terrestrial plants were swept in by the turbidity currents and were redeposited in deep water.

In the southwestern part of the San Joaquin Valley, in the Coalinga district and Kettleman Hills, the marine Pliocene is 5,000-7,000 feet (1,500-2,100 m) thick and comprises the Jacalitos and Etchegoin Formations. It is followed by the brackish-water or fresh-water Tulare Formation that bridges the upper Pliocene and lower Pleistocene. As in the Los Angeles and Ventura basins, the deposits are rather fine-grained clastics—silts below and above and sands in the middle.

In the San Francisco region farther north is a correspondingly thick but more complex array of Pliocene formations. In the Santa Cruz Mountains west of the San Andreas fault is the marine Purisima Formation about 6,000 feet (1,800 m) thick;

it is composed of volcanic sandstone, mudstone, and siliceous mudstone, which passes into shallow-water or littoral deposits toward the top. In the San Francisco Peninsula east of the San Andreas fault is the Merced Formation of similar origin, composition, and thicknesses, somewhat younger than the Purisima and including lower Pleistocene in its upper part. Across San Francisco Bay to the east, as in the Berkeley Hills, all the Pliocene is nonmarine. At the base is the Orinda Formation, 6,000 feet (1,800 m) or more thick, of fluvial, alluvial, and lacustrine sandstone and mudstone, in part conglomeratic. It is followed by the dominantly volcanic Berkeley Group, with several persistent lava units separated by clastic units. North of the bay the similar Sonoma Volcanics (Tpv) are extensive.

These Pliocene deposits are succeeded in several parts of the central Coast Ranges by coarse continental deposits which bridge the Pliocene-Pleistocene boundary. They include the Livermore Gravels, 5,000 feet (1,500 m) thick in the intermontane Livermore Valley east of the Berkeley Hills, and the equally thick but more extensive Paso Robles Formation farther south at the head of the Salinas Valley.

Most of the northern Coast Ranges north of San Francisco Bay are a terrane of Franciscan rocks, but Pliocene marine deposits encroach on them in places in embayments near the coast. Not far north of the bay are extensions of the Merced Formation, and the Ohlson Ranch Formation. Much farther north, beyond Cape Mendocino, the Wildcat Canyon Group occupies the trough of a syncline along the Eel River, where its rather fine-grained clastics attain a thickness of 12,000 feet (3,600 m).

East of the Coast Ranges in the Sacramento Valley and northern San Joaquin Valley, the Pliocene deposits are all continental. They are extensively exposed at the north end, south of Redding, the dominant sediments on the west side being the Tehama Formation and the dominant andesitic tuff on the east side of the Tuscan Formation. Farther south on the east side of the valley, near the latitude of Sacramento, is the similarly andesitic Mehrten Formation, which includes rocks of both Miocene and Pliocene ages. The andesitic debris was derived from eruptive centers in the southern part of the Cascade Range to the northeast and in the Sierra Nevada to the east.

CONTINENTAL DEPOSITS

Continental deposits of Pliocene age, which are extensive in the western interior of the United States, have several different habits: (a) sheet deposits of wide extent but small thickness (mainly in the Great Plains; (b) basin (= bolson) deposits of narrow dimensions but great thickness (in basins between the ranges in the Basin and Range province); and (c) deposits associated with and grading into contemporaneous volcanic rocks (mainly in the northwestern United States). These distinctions can serve as a basis for the following treatment of the continental deposits.

SHEET DEPOSITS

OGALLALA FORMATION[10]

By far the most extensive and continuous Pliocene continental deposit in the United States is that of the Ogallala Formation, which covers the Great Plains east of the Rocky Mountains (with only minor interruptions from later dissection) from southern South Dakota to western Texas, a distance of 800 miles (1,300 km), with a preserved width of as much as 400 miles (650 km). The Ogallala Formation has traditionally been classed as Pliocene and is so represented on the Geologic Map, but if the recently proposed upper age limit of the Miocene at 5 m.y. is accepted, all the Ogallala except for the Blancan Stage at the top would be upper Miocene.

Throughout this expanse, the Ogallala lies at or near the surface of the plains, and as shown as continuous in outcrop of the Geologic Map. In actual fact, much of the flat upper surface of the plains is masked by small thicknesses of Quaternary materials, which are shown in considerable detail on some of the State Maps—drifted sand and sand dunes, loess in the north, and occasional basins filled with various Pleistocene formations. The true outcrops of the Ogallala are mostly in the erosion scarps or "breaks" around the edges of the plains or in the walls of valleys and canyons that trench the deposit.

The Ogallala was originally more extensive east and west. Westward. it extended up to the foot of the Rocky Mountains, from which most of its sediment was derived (a narrow remnant of the deposit extending up to the mountains, known as "The Gangplank," is still preserved in southeastern Wyoming). Eastward the Ogallala thinned to a feather edge across the Midcontinent States. Erosion after the Pliocene has cut back the original edges into frayed-out escarpments or "breaks"—prominent on the east, more subdued on the west.

In the north, the Ogallala lies nearly conformably on similar earlier Tertiary continental deposits

[10]The many publications on the Ogallala Formation include Plummer (1932, p. 763-776; called the "Panhandle Formation"), Lugn (1939, p. 1255-1263), Frye and others (1956), Frye and Leonard (1957, p. 10-19; 1959), and Izett (1975, p. 201-202).

(Miocene and Oligocene, already described), but from Kansas southward it lies on the deeply eroded, channeled surfaces of Cretaceous, Triassic, and Permian strata. The formation is from 200-500 feet (60-150 m) thick and consists of poorly consolidated silt, sand, and gravel in varying proportions, with rare layers of volcanic ash, bentonite, diatomite, and fresh-water limestone. Some parts are cemented by silica, and others by lime. The most firmly lime-cemented parts are "mortar beds" or "caprock" which stand in ledges, the most prominent of which is everywhere at the top of the formation. The lime cement of these layers is caliche, a product of soil formation in a semiarid climate, and it was formed during or shortly after deposition of the sediments, as clasts of the material are reworked in the overlying Quaternary deposits.

Although the Ogallala deposits are heterogeneous, there is monotony in the heterogeneity, and there are no truly valid rock-stratigraphic subdivisions—merely gross contrasts between the lower and upper parts. Nevertheless, in Nebraska subdivisions have been recognized, named, and dignified as "formations" (although they are little more than inconstant members)—the basal Valentine, followed by the Ash Hollow, Sidney (local), and Kimball. These have paleontological basis, however, and their equivalents can be recognized as "zones" as far south as Texas. In Texas, two well-marked vertebrate faunas have served as the basis for the Clarendonian and Hemphillian Stages of the American continental Cenozoic sequence. In addition, at the top of the Ogallala at a few places in Texas are deposits separated as the Blanco Formation, which is the basis for the Blancan continental stage. The age of the Blancan has been variously assigned; weight of present opinion is that it is uppermost Pliocene (C. A. Repenning, oral communication, 1975), although in the past it has sometimes been equated with the Nebraskan or even the Kansan Stages of the Pleistocene.

Age determinations by potassium-argon and fission-track methods have been made on volcanic ash from various layers in the Ogallala Formation at localities from Nebraska to Texas. They range from 16 or 17 m.y. for layers near the base to 5 m.y. for a layer immediately above the type Hemphillian (Izett, 1975, p. 201-202).

Mammalian bones are locally abundant in the Ogallala Formation and have been collected and studied for many years. They are useful for indicating regional correlations with other parts of North America or abroad, but they are of less use for detailed stratigraphic work because of their erratic occurrence. Terrestrial gastropods are preserved in some of the more limy beds. Far more abundant are plant remains—grass seeds and nuts of small shrubs, which are present in nearly every exposure and every lithology. The plant remains can be used for zonation, and the zones can be recognized from one end of the formation to the other.

The origin of the Ogallala deposits was brilliantly expounded by Willard Johnson in a classic report of the turn of the century (Johnson, 1901, p. 612-656). He showed that they were formed on a long slope extending eastward from the Rocky Mountains, with about the same gradient (10-15 feet per mile; 1.2-1.4 m per km) and in the same semi-arid climate as at present. Streams flowed eastward across the plains, where they dropped their loads of sediments derived from erosion of the mountains. Johnson supposed that the streams spread out in distributaries on a smooth surface, but modern data on the deposit (in part from drilling) demonstrates that the streams actually flowed in valleys, which they filled with coarse material, spreading finer material across the interfluves from time to time.

With the end of the Pliocene, the aggradational epoch was terminated by climatic change and possibly by tectonic movements, so that the sheet of sediments was dissected and partly destroyed by erosion during the Pleistocene—a process which continues to the present.

Bidahochi Formation

On the opposite side of the Rocky Mountains, in northeastern Arizona and northwestern New Mexico, is the Bidahochi Formation, another sheet of deposits of about the same age as the Ogallala, although less extensive (Repenning and Irwin, 1954). (In early reports this was correlated with the Eocene Wasatch Formation and is so represented on the Geologic Map of 1932.) The Bidahochi lies on the Mesozoic formations of the Colorado Plateau in the Hopi country southwest of the Defiance Plateau and has a thickness of about 450 feet (140 m). It consists of a lower mudstone unit of lacustrine origin and an upper cross-bedded sandstone of fluviatile origin, between which are basalt flows (Tpv) in many places. The formation contains the remains of fossil beavers of middle Pliocene (Hemphillian) age.

The fluviatile parts of the Bidahochi Formation were laid down by southwestward-flowing streams and contain much detritus derived from volcanic areas farther northeast, as well as from the Rocky Mountains. The original southwestern extent of the deposit is poorly known, as much of it has been eroded, but a few outliers occur in this direction, including some on the rim of the Mogollon Plateau.

Northeast of the area of Bidahochi deposits, on the Arizona-New Mexico border, is the unfossiliferous Chuska Sandstone, also shown as a Pliocene continental deposit (Tpc) on the Geologic Map. The Chuska has sometimes been correlated with the Bidahochi but is of another character, being mainly a coarsely crossbedded dune deposit. Probably it is somewhat older, although still middle or upper Tertiary (Wright, 1956, p. 427-431).

BASIN DEPOSITS

Within the Basin and Range province of the southwestern United States the basins, or bolsons, were thickly filled during later Cenozoic time with erosional waste derived from the intervening ranges. Filling of the basins began with the initiation of the Basin and Range block-faulting in late Miocene or early Pliocene time and has continued with some interruptions to the present.

The earlier basin fill is largely of Pliocene age, as shown by fossils, although the lower parts of some of the deposits extend into the upper Miocene and the upper parts may be lower Pleistocene; they are shown as Pliocene continental deposits (Tpc) on the Geologic Map. These deposits probably underlie most of the basins, but in many areas they are masked at the surface by similar Quaternary deposits (Q). They have been uncovered mainly in areas of through-flowing drainage, such as those of the Rio Grande, Gila, Colorado, and Humboldt Rivers. On the Geologic Map, the basin areas thus appear partly in colors of gray (Q) and partly of yellow (Tpc).

The earlier basin fill is known variously as the Santa Fe Formation in New Mexico, the Gila Formation in southeastern Arizona, the Muddy Creek Formation in southern Nevada, the Humboldt Formation in northeastern Nevada, and the Salt Lake Formation in northern Utah. Nevertheless, despite their wide dispersal and diverse terminology, they share many common characters.

Close to the bordering mountains the deposits are coarse fanglomerates, but they become finer-grained farther out, and near the centers of the basins they are fine-grained sands, silts, and clays that are partly of lacustrine origin. The deposits accumulated after the great eruptions of mid-Tertiary time and are mainly non-volcanic, although minor volcanic units occur in places, mainly in the lower parts. The deposits were laid down after the first Basin and Range faulting had blocked out the basins and ranges, but before renewed faulting during Quaternary time. Renewed faulting has placed them in structural contact with the bordering ranges and has faulted and tilted them internally, the deformation being greatest close to the mountains and passing into less deformed or flat-lying contemporaneous deposits in the centers of the basins. After the earlier deposits were deformed, their upper surfaces were eroded into pediments before the Quaternary deposits were laid over them.

SANTA FE FORMATION

The Pliocene continental deposits of New Mexico, especially near the Rio Grande in the center of the State, are known as the Santa Fe Formation, which was named by Hayden in 1869 for exposures near Santa Fe, New Mexico. Much of the modern knowledge of the formation is derived from the work of Kirk Bryan and his students at Harvard University, whose many publications include those of Bryan and McCann (1937), Smith (1938), Denny (1940), and Wright (1946).

The Santa Fe Formation characterizes especially the series of structural depressions drained by the Rio Grande that extend from the San Luis Valley in southern Colorado, southward the length of New Mexico into western Texas. As shown on the Geologic Map, exposures of the Santa Fe are nearly continuous through this distance, broken only by the Quaternary alluvial cover and occasional cappings of Quaternary basalt flows (Qv). In the southwestern part of the State, discontinuous outcrops of similar deposits occur westward along the south edge of the Mogollon Plateau, to connect vaguely with the Gila Formation of southeastern Arizona.

The Santa Fe Formation is a heterogeneous body of continental deposits that was laid down in structural basins like those at present and in a similar climate. The basins were outlined by warping and faulting late in Miocene time and had somewhat different dimensions from the present ones, in some places larger. Along the margins are fanglomerates with clasts largely derived from the rocks of the adjacent mountains—Precambrian crystallines, Paleozoic and Mesozoic sediments, and older Tertiary volcanics. Farther out are well-bedded sands, and in a few places thinly stratified clays and evaporites that accumulated in playas.

The Santa Fe is unique among the basin formations in containing traces of a through-flowing river—channels containing well-rounded gravels distantly derived from the north. The gravels have been traced from the latitude of Santa Fe at least as far south as the latitude of Socorro. Although the river was ancestral to the present Rio Grande and lies near its course, it diverges widely in places, and apparently extended across modern ranges that were raised after Santa Fe time. Where the river went farther south is conjectural; it may have drained into a closed depression in northwestern Chihuahua, for through-flowing drainage to the Gulf of Mexico across the mountain barriers in the Big Bend area of Texas does not seem to have been established until after the Santa Fe epoch.

The Santa Fe contains vertebrate bones at a good many localities. The original collections made near Santa Fe have been determined to be of upper Miocene to middle Pliocene age (Barstovian, Clarendonian, and Hemphillian). Farther south only Pliocene bones have been collected, and at a few localities fossils of the Blancan Stage—a stage sometimes considered to be lower Pleistocene. The bulk of the deposit is certainly Pliocene (Tpc) and it is so represented on the Geologic Map.

Subdivisions have been recognized in the Santa Fe Formation in places, and the unit has been classed as a "group" by some authors. These are, however, merely local members, which from the very nature of the deposit could not extend far in any direction—considering the complex interfingering of different sorts of deposits laid down in contrasting environments in different parts of the basin. In the Santa Fe area, however, a lower unit, the Abiquiu, is widespread and is decidedly more tuffaceous than the overlying beds; it is usually considered to be a basal member of the Santa Fe.

Observed surface sections of the Santa Fe range from 1,000 to 4,500 feet (300-1,300 m) thick but are uncertain because of the considerable minor faulting within the formation. Well data suggest that in the centers of the deeper basins the thickness of the formation may exceed 5,000 feet (1,500 m).

The Santa Fe Formation has been considerably deformed by subsequent faulting and tilting, and the later movements have much modified the Pliocene form of the Rio Grande depression. Younger block-faulting has raised new mountains along its borders which have reduced the size of the original depression, and in a few places, as in the Valles Mountains west of Santa Fe, volcanic edifices have been built up in the original depression. The upper surface of the Santa Fe is not the original depositional surface but is a widespread planation surface (the Ortiz pediment) that was cut in early Pleistocene time.

Gila Formation

The term Gila Formation (originally called "Conglomerate") is commonly used for late Tertiary continental deposits in the intermontane basins of southeastern Arizona. It was named by Gilbert in 1875 for exposures near the Gila River in the eastern part of the State and in adjacent New Mexico. In subsequent mapping the name has been loosely applied to almost any poorly consolidated late Cenozoic continental deposit of diverse lithology and age, including (improperly) Quaternary alluvial terrace deposits at the top. As a result, some geologists class the Gila as a group, and others wish to abandon the term entirely. Nevertheless, the name is, with proper restrictions, still useful as a regional designation.

Like the deposits of the Santa Fe Formation, those of the Gila Formation include coarse fanglomerates along the margins of the basins, with clasts derived from the diverse rocks of the adjoining mountains; fine-grained, better bedded sandy deposits farther out; and fine-grained, thinly bedded playa deposits in the centers of the basins (Knechtel, 1936). Unlike the Santa Fe deposits, those of the Gila contain no trace of a through-flowing river; through-flowing drainage by the Gila and other rivers was not established in the region until after the depositional epoch during Quaternary time.

Where the Gila Formation has been studied in detail, it seems to be capable of more meaningful subdivision than the Santa Fe, and the epoch was broken into several depositional cycles with slightly different deposits and separated by unconformities. The Gila in the valley of the San Pedro River southward from its junction with the Gila River at Winkelman is now known in much detail (Heindl, 1963; Krieger and others, 1974). The oldest unit of the group, the San Manuel Formation, was deposited in a longitudinal basin west of the present axis of the San Pedro Valley. It consists of fanglomerate, and alluvial and possible playa deposits, and attains a thickness of 5,000 feet (1,500 m). It is notable for its lenses of megabreccia composed of large masses of the hard pre-Tertiary rocks, which were probably carried into the basin in gigantic landslips. An overlying tuff unit has been dated radiometrically as middle Miocene, so that the San Manuel deposits are evidently lower Miocene. Unconformably on the San Manuel at the north end of the valley is the Big Dome Formation, a coarse alluvial deposit about 600 feet (180 m) thick, which was laid down in the present structural depression. It is younger than the radiometrically dated middle Miocene tuff, and radiometric dates on interbedded tuffs suggest an upper Miocene age. Following the Big Dome epoch, the structural depression was further restricted by faulting, and the alluvial and lake-bed deposits of the Quiburis

Formation were deposited along the axis of the valley. They are about 1,500 feet (450 m) thick and contain middle Pliocene (Hemphillian) mammalian bones.

Other areas of the Gila have not been studied in as much detail as the one just described, so that the regional history and extent of subdivisions of the Gila are still imperfectly known. Deposits with Pliocene bones occur southward in the San Pedro Valley nearly to the Mexican border and indicate the wide extent of the Quiburis in this direction. In the Safford Valley farther east, the main body of the Gila, or "Solomonsville beds," about 2,000 feet (600 m) thick, also contains Pliocene fossils (Wood, 1959, p. 60) but is underlain unconformably by the earlier "Bonita beds" of massive volcanic conglomerate. Above are the "Frye Mesa beds" of bouldery conglomerate that fringe the edges of the bordering mountains and are clearly Pleistocene. All the Gila of southeastern Arizona is indicated as Pliocene continental deposits (Tpc) on the Geologic Map.

Drilling in the basins of southwestern Arizona indicates the presence of evaporites in the Pliocene deposits, suggesting a tenuous connection with the sea in the Gulf of California.

Muddy Creek Formation

The late Tertiary basin deposits of southern Nevada are the Muddy Creek Formation (Longwell and others, 1965, p. 48-49), typically developed in Muddy Valley northeast of Las Vegas. The Muddy Creek occurs in all the intermontane depressions near the Colorado River from Las Vegas eastward to the Grand Wash Cliffs at the edge of the Colorado Plateau and has been partly submerged by the waters of Lake Mead.

Like the basin deposits previously described, the Muddy Creek consists of fanglomerate and other coarse deposits near the mountain borders, passing basinward into well-stratified deposits of sandstone, siltstone, and clay. In the centers of some of the basins are evaporite deposits—chiefly gypsum, but with thick beds of rock salt in the Virgin Valley. Bedded manganese oxides occur at one place, and fresh-water limestone in others. One or two basalt flows are interbedded. Except near some of the bordering faults, the formation is virtually undeformed and flat-lying. The age of the Muddy Creek is uncertain, as fossil remains are scarce; it is probably mainly Pliocene, although a Miocene age has been ascribed to some of the vertebrate material. The Muddy Creek Formation is 2,000 feet (600 m) or more thick.

The Muddy Creek was deposited in an arid environment not unlike that of the present intermontane basins in a region of interior drainage which was ponded in places to produce lacustrine deposits such as the evaporites and fresh-water limestones. All the sediments are locally derived, and there is no indication of any through-flowing river, such as the Colorado River that now traverses the area (Longwell, 1946, p. 821-826). Deposits of the Colorado River, including well-rounded foreign gravels, lie on the eroded surface of the Muddy Creek and were deposited during several stages, none of which are older than Pleistocene.

Deposits like those of the Muddy Creek occur in the intermontane basins northward from the Colorado River into eastern Nevada and adjacent southwestern Utah. Part of these deposits is the Panaca Formation, from which Pliocene vertebrate bones have been collected.

Humboldt Formation

The late Tertiary Basin deposits of northeastern Nevada are the Humboldt Formation (Sharp, 1939), which was named by Clarence King in 1878 for exposures in the upper drainage of the Humboldt River. It is well exposed near the river, as in the vicinity of Elko and the Ruby Mountains, and occurs in most of the intermontane basins northward to the edge of the State. South of the Humboldt River the formation is mostly concealed by Quaternary basin deposits. In some publications the term Humboldt has been loosely applied to almost any of the later Tertiary deposits of the region, but some earlier Tertiary deposits are not properly a part of it and should be excluded. Except where these occur, the formation lies unconformably on the pre-Tertiary rocks of the bordering ranges.

The Humboldt Formation is about 3,000 feet (900 m) thick and consists of fanglomerate and conglomerate near the mountains, which pass upward and outward into sandstone, mudstone, and siltstone, much of which is tuffaceous. It is of fluviatile and lacustrine origin. The fanglomerates near the Ruby Mountains consist of clasts of Paleozoic limestone below, passing up into clasts of crystalline rocks, indicating progressive unroofing of the range, probably by uplift along block faults during deposition of the formation. Other ranges in the region were probably also undergoing block uplift during Humboldt time. At the margins of the deposit, as at Palisades Canyon on the Humboldt River west of Elko, rhyolite flows intertongue with the upper part of the deposits.

The Humboldt Formation contains rather abundant vertebrates, as well as fresh-water invertebrates and plants. The vertebrates are generally ascribed a late Miocene age, and there is no indication of any of Pliocene age. Nevertheless, it is shown along with the other basin deposits as a Pliocene continental deposit (Tpc) on the Geologic Map.

Salt Lake Formation

In northeastern Utah and southeastern Idaho the late Tertiary basin deposits are the Salt Lake Formation, named by Hayden in 1869. It is exposed on the flanks of the Wasatch Range north of Salt Lake City and between other ranges farther north, as far as the Snake River Plain. The formation consists of tuff, tuffaceous sandstone, shale, and marl, partly of fluviatile and partly of lacustrine origin. Exposed sections 1,500 feet (450 m) thick are common, and the total may exceed 3,000 feet (900 m). Subdivisions have been recognized in some areas, and units of several different ages may be present, although the bulk of the formation is believed to be Pliocene. The Salt Lake lies unconformably on the Wasatch and other Eocene continental deposits, and in some of the valleys it is overlain by sheets of basalt of Quaternary age. In some of the ranges the formation has been much disturbed and offset by later block-faulting, but in other areas it is little deformed.

DEPOSITS ASSOCIATED WITH VOLCANIC ROCKS

Pliocene continental deposits (Tpc) are shown on the Geologic Map in many parts of the volcanic province of the northwestern United States, where they are associated with and grade into Pliocene volcanic rocks and are not ordinarily basin-fill deposits like the group just described. In many areas they are merely end-members of a sequence ranging from lava flows, through ash-flow tuffs and tuffs, to strata more clearly sedimentary, and thus they have no special designations. In some places, however, they have more stratigraphic entity and have been given formation names.

Idaho Group

In the western third of the Snake River Plain of southwestern Idaho is a complex sequence of Pliocene and early Pleistocene continental deposits and interbedded volcanics, the Idaho Group, which accumulated in this northwest-trending segment during its downwarping and downfaulting (Malde and Powers, 1962, p. 1201-1212).

Beneath the Idaho Group, especially on its southern border, are the largely felsic Idavada Volcanics (Tpf) whose sedimentary members contain plants and other fossils of lower Pliocene age. Above the group, especially toward the east, are the basalt flows of the Snake River Group (Qv) of Pleistocene and Holocene age.

The Idaho Group itself is a body of fluviatile and lacustrine deposits and interbedded basalt flows about 3,000 feet (500 m) thick and of middle and upper Pliocene and lower Pleistocene age, which is divisible into a set of named formations. All the formations are lenticular and are mostly unconformable with each other because of progressive downwarping and downfaulting of the plain during accumulation. All the sedimentary units are rather abundantly fossiliferous and contain vertebrate bones, plants, and fresh-water mollusks which provide many data on the different ages. The subdivisions are the Poison Creek Formation, Banbury Basalt, and Chalk Hills Formation, all of Pliocene age; the Glens Ferry Formation which bridges the Pliocene-Pleistocene boundary; and the Tuana Gravel, Bruneau Formation, and Black Mesa Gravel of Pleistocene age.

Other Formations

On the eastern flank of the Cascade Range in central Washington is the Ellensburg Formation, a fine- to coarse-grained clastic deposit, largely derived from erosion of the middle Tertiary andesitic volcanics of the Cascades (Waters, 1955, p. 670–675). The Ellensburg overlies the Yakima Basalt of the Columbia River Group and contains in its lower part thin interbedded basalt flows like those beneath. Eastward it interfingers with and is apparently largely replaced by the upper basalts of the Columbia River Group. The Ellensburg contains plants, fresh-water gastropods, and vertebrates of early Pliocene age.

Along the valley of the John Day River, in the Blue Mountains uplift of northeastern Oregon, is the Rattlesnake Formation, composed of fanglomerate, bouldery gravel, and welded tuff. It lies unconformably on the Miocene and earlier sedimentary and volcanic rocks of the region, and contains middle Miocene (Hemphillian) vertebrates, but its upper part may extend into the Pliocene.

In western Nevada are the Truckee Formation of the Reno area (Thompson and White, 1964, p. 16–17) and the Esmeralda Formation of Esmeralda County farther southeast (Robinson and others, 1968). Both are late Tertiary fluviatile and lacustrine deposits, laid down in disconnected structural basins that correspond closely to the modern blockfaulted depressions. Both formations contain large volumes of volcanic debris—basaltic and andesitic in the Truckee, rhyolitic in the Esmeralda. This debris is intermingled with non-volcanic sedimentary components, including siltstone, diatomite, beds of coal (in the Esmeralda), and pebble conglomerates formed of clasts of the pre-Tertiary rocks. The Truckee Formation is at least 2,000 feet (600 m) thick, and the Esmeralda in places attains 9,000 feet (2,700 m). The Truckee Formation interfingers with the upper part of the andesitic Kate Peak Formation and is overlain by younger basalts. The Esmeralda interfingers with and is overlain by the volcanic rocks of the Silver Peak center. The Truckee contains fossil plants of middle Pliocene age. Fossil remains in the Esmeralda are more diverse, and include plants, mammals, fish, ostracodes, and mollusks of Hemingfordian, Barstovian, and Clarendonian ages; radiometric dates by the K/Ar method range from 13 to 4 m.y., or from late Miocene to late Pliocene.

In eastern California, east of the south end of the Sierra Nevada, is the Ricardo Formation of continental and lacustrine sediments and interbedded lavas and tuffs, which attains a thickness of 7,000 feet (2,100 m) and contains lower Pliocene (Clarendonian) vertebrates.

QUATERNARY SYSTEM

Quaternary deposits are only partly represented on the Geologic Map of the United States, because they are primarily a surficial mantle over the pre-Quaternary bedrock—representation of which is the principal objective of the map. The appropriate place for a complete representation of the Quaternary deposits is on a surficial geology map, several of which have been published of different parts of the country. The U.S. Geological Survey is now planning a surficial geology map of the whole United States, as a companion to the present geologic map.

The Geologic Map of the United States does not represent the glacial and other deposits of Pleistocene age that blanket large parts of the Northern Interior States, nor the loess and drifted sand that are extensive in some other places. In such areas the bedrock may be partly or wholly concealed, and its representation must be by subcrop or subdrift mapping, based more on the results of drilling and geophysical data than on outcrops. In the Northern Interior States we have, however, marked the limits of the earlier and later Pleistocene glaciations, to suggest areas in which the bedrock is likely to be extensively concealed.

The Geologic Map does, however, represent the Quaternary deposits along the Atlantic and Gulf Coastal Plains and in intermontane areas in the West, where they are an essential feature of the bedrock pattern (fig. 5). In such areas the Quaternary deposits attain sizeable thicknesses, and in many areas the bedrock pattern beneath them is poorly known or unknown. In the Coastal Plains of the Eastern United States, the Quaternary deposits are divided into the Pleistocene (Qp) and Holocene (Qh) Series. The Quaternary deposits of the Western United States are not separated on the Geologic Map and are represented as an undifferentiated unit (Q). In many of these areas, the respective outcrops of the Pleistocene and Holocene Series would be too small to show on the scale of the map, and the differentiation between them has not been made on many of the source maps.

GULF COASTAL PLAIN

MISSISSIPPI EMBAYMENT

By far the largest area of Quaternary deposits in the Coastal Plains is that in the Mississippi Embayment, which extends northward from the Louisiana coast for 600 miles (950 km) to southern Illinois. Extending centrally through the embayment is the alluvial valley of the Mississippi River, filled largely by Holocene deposits, flanked on one or both sides by Pleistocene terrace and other upland deposits.

Much of our knowledge of the alluvial valley we owe to the classic memoir of Fisk (1944), in which the modern landforms and the processes at work on them are ably set forth, and an attempt made to reconstruct its earlier Quaternary history. Further investigations, and the accumulation of more data since publication of this memoir, have resulted in considerable modifications of Fisk's proposed history (Durham and others, 1967; Saucier, 1974). A major change that affects representation on the Geologic Map is the reassignment of the lower alluvial terraces in the valley from after the end of the last glacial period, 10,000 to 12,000 years ago, to earlier periods, some as early as the Sangamon Interglacial Stage about 100,000 years ago; all the terraces in the valley are mapped as Pleistocene rather than Holocene.

The oldest continental deposits near the Mississippi River valley are the Citronelle Formation of probable late Pliocene age, already described, which forms a coastward-dipping body of sediments in the uplands to the east and west. In addition, Fisk identified two high-level terrace deposits and surfaces on the uplands of supposed early Pleistocene age, the Williana and Bentley. While it is true that vague, deeply dissected surfaces can be recognized in the uplands, the surfaces were probably cut from

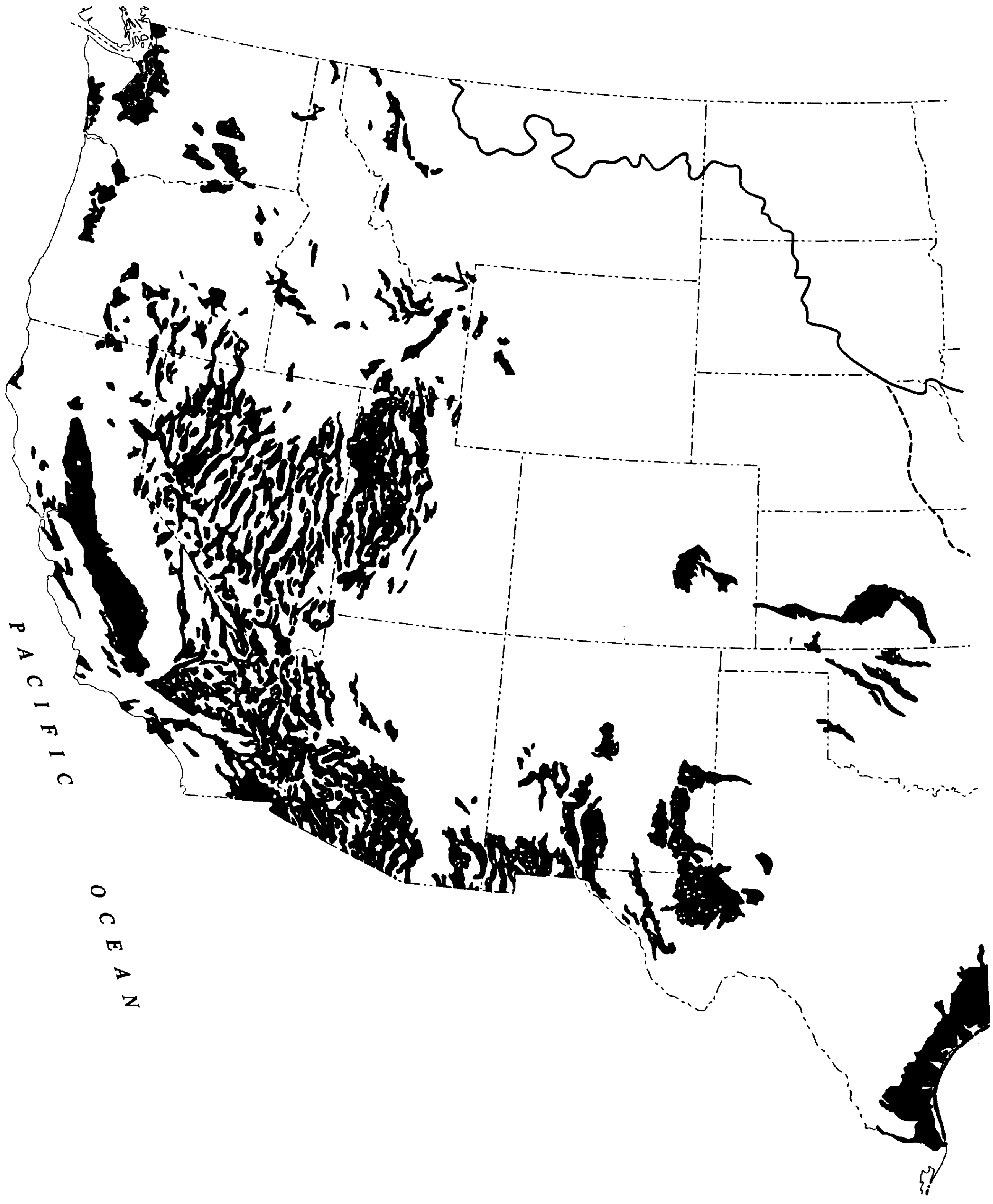

FIGURE 5.—Map of the United States showing surface distribution of Quaternary deposits as represented on Geologic Map of the United States (units Q, Qp, Qh). Within the lines in the northern part of the map, the pre-Quaternary rocks are extensively covered by Pleistocene glacial deposits which are not mapped (solid line, limit of Wisconsin Glaciation, broken line limit of earlier glaciations).

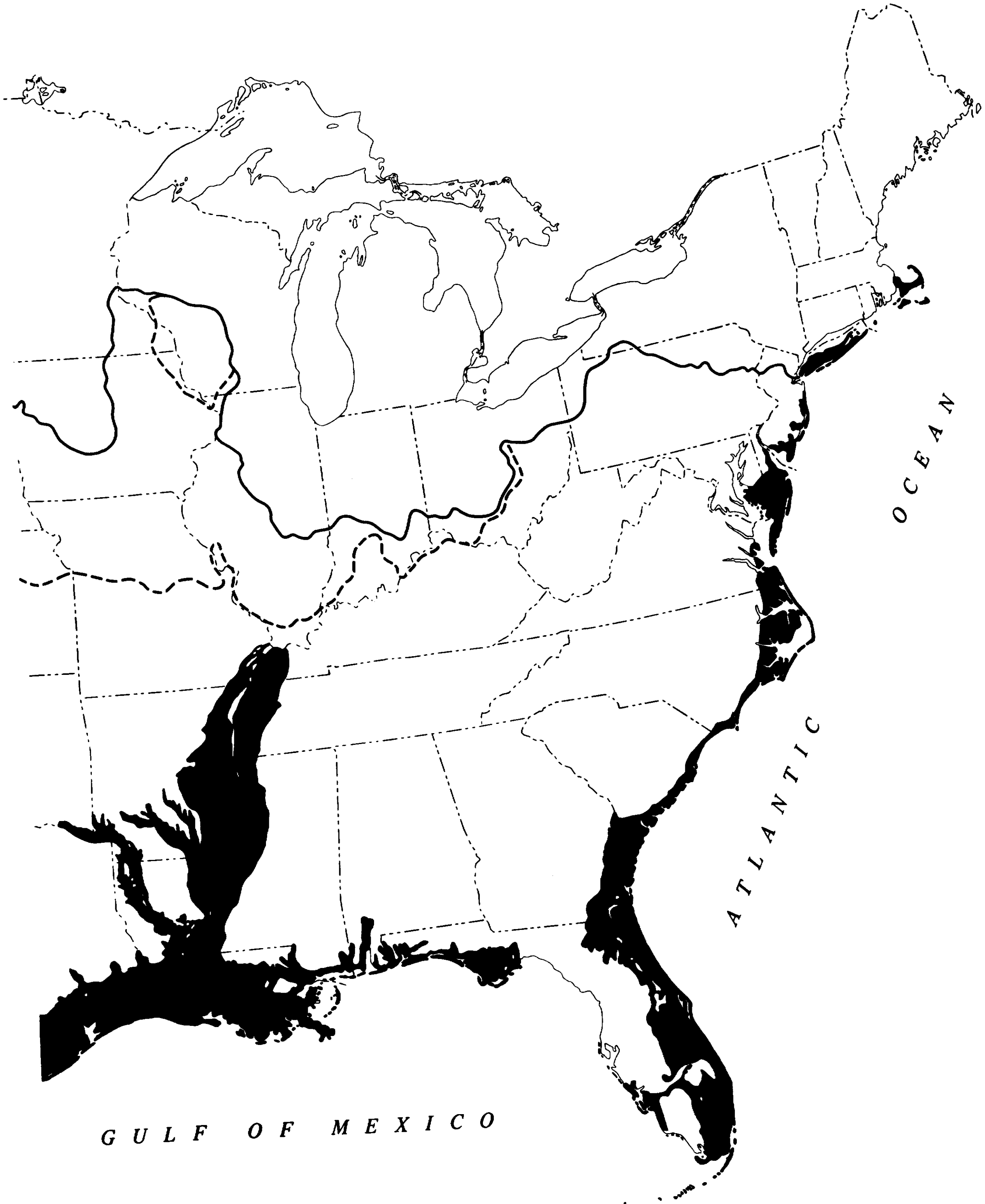

FIGURE 5.—Continued.

time to time in the Citronelle deposits. The decipherable history of the valley begins with the Montgomery Terrace Formation of the Yarmouth Interglacial Stage (post-Kansan).

The development of the valley was controlled by the glacial and interglacial periods of Pleistocene time. During glaciations, sea-level was lowered as much as 400 or 450 feet (120–140 m), resulting in the cutting of a system of fairly deep valleys in the bedrock floor. Their existence, which was first suspected as early as 1881 by drilling in the alluvium, have been abundantly documented since by a closer net of drill holes. During each interglacial stage, sea-level rose to nearly its original level, and the valley was aggraded; the streams, at first heavily loaded with glacial outwash, had a braided pattern, and passed later into a meander-belt pattern. During the braided stream stage, silt was carried eastward by the wind and deposited as loess on the uplands on this side of the valley. During last post-glacial, or Holocene cycle, the river has now attained the meander-belt stage throughout the alluvial valley (Qh). The earlier aggradational stages are represented by the terrace deposits that border the valley (Qp).

The oldest identifiable Pleistocene terrace formation (Qp) is the Montgomery, of inferred Yarmouth age, represented by deeply weathered, dissected remnants. Its deposits attain thicknesses of 300 or 400 feet (90–120 m), and slope seaward at a rate of 3-4 feet per mile (0.6–0.7 m per km), probably passing beneath the succeeding Prairie Terrace Formation at steadily increasing depths. The Prairie Terrace Formation, of presumed Sangamon age, is far more extensive, especially in the coastal belt of southern Louisiana, and its surface includes meander-belt deposits inland, and deltaic plains, relict lagoons, and barrier islands near the coast. At levels below the Prairie Terrace are smaller terraces formed during the Wisconsin glacial and interglacial substages, including the fluvial Deweyville Terrace in upstream areas and various braided-stream terraces within the alluvial valley.

The Holocene deposits (Qp) of the alluvial valley include meander belts formed at different times by the Mississippi River and its tributaries, as they shifted this way and that across the valley. Between the meander belts are back-swamp deposits. Downstream, the deposits form deltaic plains with branching distributaries and along the coast chenier plains with elongate beach ridges ("cheniers").

OTHER AREAS

West of the Mississippi Embayment, in southwestern Louisiana and in Texas, a belt of Quaternary deposits 40–80 miles (65–130 km) wide lies between the Tertiary outcrops and the coast. Their surfaces are a succession of broad plains or benches stepped down coastward, which express a set of formations. Stratigraphic terminology in Texas antedates that in the Mississippi alluvial valley and elsewhere in Louisiana; broader correlations between them are clear, but there is disagreement on details (compare Doering, 1956, p. 1,831–1,840; and Bernard and LeBlanc, 1965, p. 176–179). Traditionally, the Pleistocene has been divided into the Lissie and Beaumont Formations. On the Houston and Beaumont sheets of the Geologic Atlas of Texas (1968), the Lissie is divided into the Bentley and Montgomery Formations, supposedly correlative with the Louisiana units, and the Beaumont is correlated with the Prairie Formation of Louisiana, with which it is physically continuous; in addition, the Deweyville Terrace Formation is recognized along the upstream parts of the major rivers, as it is in Louisiana.

This segment of the Coastal Plain differs from that in the Mississippi Embayment in that none of its rivers headed in a glaciated area farther north, so that direct glacial control was lacking; otherwise, the deposits and conditions of deposition were much the same. Most of the plains were deltaic, and the surface of the Beaumont, especially, is marked by branching distributary channels whose natural levees are sandy deposits separated by areas of clay deposits. Toward the coast, the Beaumont passes into brackish-water and near-shore deposits which contain many shell banks.

Holocene deposits are confined to offshore bars and to broad belts of stream alluvium that extend far up the major river valleys. On the Geologic Map, these alluvial belts are arbitrarily cut off about 100 miles (160 km) from the coast so as not to obscure the bedrock formations, but they actually extend nearly to the inner edge of the Coastal Plain. In south Texas, not far north of the Rio Grande, an extensive body of drifted sand spreads inland over the Pleistocene deposits and is mapped with the Holocene.

East of the Mississippi Embayment, the Citronelle and older Tertiary formations reach close to the coast so that the Pleistocene deposits are mostly missing and the Holocene is represented by only a narrow coastal strip. The only exception is in northwestern Florida where the Appalachicola River has built a delta which includes several Pleistocene terraces that are seemingly correlative with those farther west (Doering, 1956, p. 1,854–1,858).

ATLANTIC COASTAL PLAIN

Representation of the Quaternary of the Atlantic Coastal Plain on the Geologic Map is based, for the most part, on the available State Geologic Maps. These maps show as Quaternary a belt of varying width along the coast where the Tertiary rocks farther inland are no longer exposed, and they ignore areas of Quaternary deposits farther inland where they are thinner and more discontinuous. This procedure is desirable on the Geologic Map, whose purpose is to emphasize the pre-Quaternary bedrock. Nevertheless, as examination of the literature of the Quaternary of the Atlantic Coastal Plain will show, the results are empirical rather than morphological, as explained below.

The only modifications of representation from the source maps were made in Maryland, Delaware, and New Jersey, and in northeastern Florida. In the first three States, the inland extent of the Quaternary deposits is shown in much greater detail on the State Maps than farther south, interspersed with outcrops of the Tertiary rocks. Here, the same procedure was adopted as farther south, and the Quaternary was mapped only beyond the limits of Tertiary outcrops. For the actual extent of the Quaternary in these States, see King and Beikman (1974, fig. 15, p. 37).

In northeastern Florida, the State Map (1964) indicates the Quaternary as "Recent and Pleistocene; several lower marine and estuarine terrace deposits." In this area, further subdivision was made on the basis of MacNeil's map (1950, pl. 19), which represents the Quaternary terrace formations and their shorelines. Shown as Pleistocene were the higher terrace formations—the Okefenokee at about 150 feet (45 m), the Wicomico at about 100 feet (30 m), and the Pamlico at about 30 feet (10 m). Shown as Holocene were the Silver Bluff at about 10 feet (3 m), which MacNeil classes as post-Wisconsin, and surfaces below it. The results are somewhat questionable, but no better map representation was available to us.

On the Geologic Map, the Holocene of the Atlantic Coastal Plain is represented as a strip along the coast from Florida through Georgia into South Carolina; farther north all the Quaternary is mapped as Pleistocene. It is true that Holocene deposits form the offshore bars here, as well as narrow strips along the inlets, but in areas too small to separate. Moreover, the Pleistocene and Holocene are not separated on many of the source maps. Beyond New Jersey, on Long Island, Martha's Vineyard, Nantucket, and Cape Cod, the Quaternary deposits are clearly a product of the Pleistocene glacial period—the massive Wisconsin terminal moraines and associated deposits.

An extensive literature on the Quaternary deposits of the Atlantic Coastal Plain exists, and geologists have much debated their meaning, with confusing results—as to what parts are marine and what parts continental, as to whether they are classifiable according to altitude (that is, whether they formed on surfaces representing different stands of the sea during the Pleistocene), their relation to glaciation, and their possible relation to crustal warping. The publications up to 1940 were summarized by Flint (1940), and since then still other views have been expressed (for example, MacNeil, 1950; Doering, 1960; and Alt and Brooks, 1965), some of them widely divergent.

The terrace concept was championed especially by C. W. Cooke, who recognized as many as seven surfaces forming a descending flight from as high as 270 feet (90 m) to sea-level. All the surfaces were supposed to be unwarped and horizontal from one end of the Coastal Plain to the other and to have been formed by marine invasions during the Pleistocene glacial period, each marine submergence being less than the one preceding, for reasons not entirely clear. These interpretations have been accepted only in part by other geologists.

In Virginia and North Carolina two scarps created by marine erosion are widely traceable—the Surry at 90 feet (27 m) and the Suffolk at 25 feet (7.5 m). Above the Surry there is no convincing evidence of any marine deposits (Flint, 1940, p. 777). All the Quaternary shown on the Geologic Map in these States is below the Suffolk scarp. In Florida and Georgia, evidence of marine submergence to higher levels is better documented; MacNeil (1950, p. 99) reports evidence of marine scarps, bars, and deposits at altitudes as high as 150 feet (45 m). These higher features are shown as Pleistocene on the Geologic Map. For this area a strongly dissenting view is taken by Alt and Brooks (1965, p. 407-410) who recognize shorelines as high as 250 feet (75 m), but interpret the higher ones as of Miocene and Pliocene age and concede as Pleistocene only those below 30 feet (10 m).

The only marine surface and deposit which can definitely be correlated with the glacial events to the north is the Cape May Formation of coastal New Jersey, standing at 30 feet (10 m), which can be traced into Sangamon interglacial deposits (between the Illinoisan and Wisconsin glaciations).

GREAT PLAINS

For the most part, Quaternary deposits in the continental interior east of the Rocky Mountains are not shown on the Geologic Map, but some are represented in the southern part of the Great Plains, part of which are classed as Pleistocene, part as undifferentiated Quaternary, as explained below. Omitted from the map are the sand hills of northwestern Nebraska, of Quaternary age, which lie on the Pliocene Ogallala Formation (King and Beikman, 1974, fig. 14, p. 35), and the glacial deposits farther north which form a nearly complete blanket over the bedrock east of the Missouri River (King and Beikman, 1974, fig. 11, p. 31). The extent of the glacial deposits is suggested on the Geologic Map by the lines representing the limits of glaciation.

PLEISTOCENE

The largest area shown as Pleistocene is an irregularly shaped body in southeastern Colorado, whose deposits have commonly been shown as Pliocene Ogallala Formation on published geologic maps (although they are shown as Miocene on the Geologic Map of North America of 1965, for reasons not apparent). The unit lies on an eastward-sloping surface on the divide north of the Arkansas River that projects in low scarps above the surrounding lowlands. This surface is distinctly lower than that of the Ogallala Formation to the east—more than 500 feet (150 m) as projected—and must be a younger feature.

The deposits which underlie the western part of the surface are the Nussbaum Formation, named by Gilbert in 1897, which crops out around its edges. The surface itself is mantled by windblown sand, which extends to the east end of the area; the eastward extent of the Nussbaum beneath the surface is uncertain. The Nussbaum is an alluvial deposit, much less consolidated than the Ogallala deposits and more like the Quaternary alluvium on lower surfaces in the area (Scott, 1963). No diagnostic fossils have been found in the Nussbaum, but it seems to be the first member of the alluvial sequence and to be of early Pleistocene age. The area is accordingly marked as Pleistocene (Qp) on the Geologic Map.

A smaller area of Pleistocene is indicated farther east, in the Great Plains of Meade County at the south edge of Kansas. The deposits of the area are the Meade Formation, a body of sand and gravel that fills a basinlike area to a thickness of more than 200 feet (60 m) (Frye, 1942, p. 103-109). It contains vertebrates and mollusks of early Pleistocene (Nebraskan) age, and it is overlain by one of the layers of the widespread Pearlette Ash of Kansan age. Pleistocene deposits occur on the Tertiary and older rocks in many other places in this part of the Great Plains, but they do not attain the thickness or have the basinlike form of those in the Meade County area.

Another area of Pleistocene is indicated at the south edge of the Great Plains west of Big Spring, Texas. This was the site of Lake Lomax, that occupied a basin on the surface of the Ogallala Formation during late Pleistocene (Wisconsin) time (Frye and Leonard, 1964, p. 16-19). The basin was probably created by subsidence, resulting from solution of the underlying bedrock. Similar but smaller basins containing Pleistocene lake deposits, termed the Tahoka Formation, are scattered here and there over the surface of the Great Plains (= Llano Estacado) in Texas, but they are not represented on the Geologic Map.

South of Lake Lomax a large area of Pleistocene is shown on the Geologic Map surrounded by Lower Cretaceous limestones of the Edwards Plateau. This area is usually shown as Ogallala Formation on published geologic maps, but the deposits which cover its surface are only a few feet thick, are locally derived, and are probably younger.

A final area is indicated as Pleistocene on the Geologic Map in southeastern New Mexico, between the Pecos River and the Ogallala Formation of the Great Plains at the east edge of the State. It is shown on the New Mexico Map (1965) as "Qab—Alluvium and bolson deposits and other surficial deposits." The area is an irregular surface of intermediate height between the Roswell basin along the Pecos and the Great Plains to the east. Most of it is covered with heterogeneous surface deposits, including windblown sand and caliche, probably of variable thickness due to solution-collapse of the underlying bedrock. To distinguish these deposits from the alluvium along the Pecos River they are tentatively shown as Pleistocene (Qp) on the Geologic Map.

UNDIFFERENTIATED QUATERNARY

The Roswell and Toyah Basins along the Pecos River in southeastern New Mexico and western Texas much resemble the intermontane basins farther west, except that they are not defined by faults and other structures but have been produced by erosional excavation that has been accentuated by collapse resulting from solution of salt and other evaporites in the underlying Permian bedrock.

The Roswell Basin in New Mexico, the smaller and better defined of the two, is bounded on the west by the limestone foothills of the Sacramento Mountains and on the east by lower scarps of Permian redbeds and Triassic sandstones. Southward, near Carlsbad, New Mexico, the Pecos River flows from the basin onto Permian and Triassic bedrock, before passing into the Toyah Basin in Texas. The Toyah Basin is much larger, more irregular, and less well defined; it is bounded by the trans-Pecos mountains on the west and by Lower Cretaceous limestones of the Edwards Plateau on the south and east. At its lower end, the Pecos again flows on bedrock in a canyon in the Edwards Plateau to its junction with the Rio Grande.

The surface cover of the Roswell Basin is complete, but that in the western part of the Toyah Basin is interrupted by many outcrops of bedrock. The surface materials in the two basins form a succession of descending terraces whose formation has been ascribed to events during the glacial period (Fiedler and Nye, 1933, p. 106-113) The Quaternary deposits beneath the surface have a variable thickness, commonly more than 100 feet (30 m), but are much thicker in places. Drill holes indicate depths of more than 300 feet (90 m) in parts of the Roswell Basin, and well over 500 feet (150 m) in parts of the Toyah Basin. The deepest fill in the Toyah Basin is along its northeast side, where there are few rock outcrops and where the underlying Permian salt beds were originally thickest (Maley and Huffington, 1953). The thick alluvial fill was produced in areas of deep circulation of ground water and consequent salt solution and collapse. Collapse due to solution is evident near the Pecos River at the lower end of the Toyah Basin, where the otherwise flat-lying Lower Cretaceous limestones dip steeply and erratically toward the valley.

East of the Great Plains in Kansas and Oklahoma, the source maps indicate broad, lengthy strips of Quaternary along the Arkansas, Cimmaron, Canadian, and other rivers. These appear to be chiefly windblown sand and silt derived from the river valleys. We have been reluctant to mark these surficial deposits on the Geologic Map but have shown the larger strips. The strip along the Arkansas River, especially, is too extensive to ignore, as it interrupts the continuity of the bedrock formations whose patterns beneath are conjectural.

CALIFORNIA[11]

The nonglacial Quaternary of California exceeds in variety and complexity any other in the United States—marine deposits in coastal embayments and uplifted marine terraces along the coasts, terrestrial deposits in the inland basins, and indications of major orogeny within the period. Moreover, the sequence of glacial deposits in the Sierra Nevada can be related at least tenuously with nonglacial sequences in the nearby lowlands. Nevertheless, the system is shown as an undifferentiated unit (Q) on the Geologic Map, and a subdivision into Pleistocene and Holocene Series is not attempted as it was in the Mississippi Embayment. Data for such a subdivision are available in most areas, but the results would be too minute and complex for the scale of the map. Also, the marine lower Pleistocene of southern California, which is conformable on the Pliocene and forms a narrow band of outcrop adjacent to it, is for convenience mapped with the Pliocene (Tp).

The marine Pleistocene is best developed in the Ventura and Los Angeles basins of southern California. In this region, a major structural unconformity has long been known between deformed strata and nearly undisturbed overlying deposits, which Lawson (1893) first supposed to mark the Tertiary-Quaternary boundary. Later, however, paleontologists determined that the upper part of the deformed sequence was also Pleistocene, so that the period of orogeny indicated by the unconformity actually lay within the Pleistocene Epoch. Paleontological differentiation of Pliocene and Pleistocene in the region was based on Lyellian principles of relative percentages of modern genera and species, principally of the marine megafossils (Woodring, 1952, p. 402), but it has since been largely confirmed by planktonic Foraminifera.

The classic section in the region is that in the Palos Verdes Hills on the coast southwest of the Los Angeles basin, where marine Pleistocene fossils were first reported by Ralph Arnold in 1903 and more fully documented in later reports (for example, Woodring and others, 1946). Here, the lower Pleistocene is about 600 feet (180 m) thick and comprises the Lomita Marl, Tims Point Silt, and San Pedro Sand. These beds have been tilted and are overlain unconformably by flat-lying upper Pleistocene deposits, including the Palos Verdes Sand, on uplifted marine terraces. Middle Pleistocene is missing. Northeastward in the Los Angeles basin, the Pleistocene thickens in subsurface to 3,000 feet (900 m) and the mid-Pleistocene hiatus may disappear.

Most of the fossils in the lower Pleistocene of the Palos Verdes Hills are northern cool-water forms, a fact which was once thought to indicate the onset of glacial conditions, but which might well reflect depth of water and coastal upwellings. A radiometric date of three million years on glauconite from the Lomita Marl, obtained by J. S. Obradovich, is disconcertingly old for Pleistocene and is suspect for a number of reasons.

In the Ventura basin to the northwest, surface sections of the Pleistocene are considerably thicker than in the Palos Verdes Hills—as much as 2,500 feet (760 m), a sizeable figure but modest compared with the 15,000 feet (4,500 m) or so of the underlying Pliocene. The lower Pleistocene follows conform-

[11] The Quaternary of California is summarized by Wahrhaftig and Birman (1965). An earlier summary by Reed (1933, p. 255-273) is of historical interest.

ably on the Pliocene Pico Formation and comprises the Santa Barbara and San Pedro Formations. Here, the mid-Pleistocene unconformity is even more pronounced than in the Los Angeles basin. The Pliocene and lower Pleistocene are steeply upended and even overturned and are overlain with right-angled unconformity by upper Pleistocene terrace deposits. As explained earlier (p. 32) the orogeny implied by this unconformity, although impressive here and at some other places, is merely a local and terminal event in a long sequence of tectonic instability.

Farther north, in the San Francisco Peninsula, is the marine Merced Formation, whose upper part, conformable on the lower, is of early Pleistocene age. Both the lower and upper Merced are moderately deformed.

The marine upper Pleistocene of the coastal area mostly forms the capping of flights of uplifted wave-cut terraces. In the Palos Verdes Hills there are 13 marine terraces between sea-level and 1,300 feet (400 m). The number and maximum height of the terraces varies from one coastal segment to another, and their altitudes vary as a result of warping; the cover of marine fossiliferous deposits is best preserved on the lower surfaces. Some of the sea-level changes implied by the terraces are probably attributable to subtraction and addition of sea water during the glacial and interglacial stages, but the uplift of the higher terraces is more likely tectonic. The lowest terrace, standing at about 100 feet (30 m) has commonly been correlated with the Sangamon Interglacial Stage, and near Santa Cruz has yielded radiometric ages of about 110,000 years. An unsolved problem is that the terraces are restricted to the present coastal slopes; none of the nearby interior valleys show any indications of the deep submergence or successive marine planations implied by the coastal terraces.

Most of the Pleistocene deposits just described are only indifferently represented on the Geologic Map. On the map, by far the largest area of Quaternary is that in the San Joaquin and Sacramento Valleys and consists of varied terrestrial deposits of different ages. The total thickness of Quaternary deposits attains 15,000 feet (4,500 m) in the southern part of the San Joaquin Valley but is much less farther north.

On the southwest side of the San Joaquin Valley (as near the Kettleman Hills) is the lower Pleistocene Tulare Formation, a lacustrine or marsh deposit containing fresh-water mollusks. It conformably overlies the marine Pliocene Etchegoin and San Joaquin Formations and was deformed with them along the anticlines along the edge of the valley during mid-Pleistocene time. The deformation fades out northeastward across the valley, although an unconformity persists. Near the middle of the Tulare in subsurface is a thin, widespread, diatomaceous silty clay layer, the Corcoran Clay Member. On the east side of the valley this is overlain locally by pumiceous ash which has been dated by the K/Ar method at 600,000 years.

On the northeast side of the San Joaquin Valley are a set of alluvial formations derived mainly from erosion of the Sierra Nevada. Below is the Turlock Lake Formation, which is traceable in subsurface into the Tulare Formation, followed by the middle and late Pleistocene Riverband and Modesto Formations. The latter is essentially undeformed, but it stands in low benches above the Holocene alluvium of the present valley bottoms.

The Quaternary deposits of the Sacramento Valley to the north are much thinner and contain some volcanic detritus. They lie unconformably on the eroded surfaces of the Tertiary and older rocks.

BASIN AND RANGE PROVINCE[12]

Undifferentiated Quaternary (Q) is shown on the Geologic Map in most of the intermontane basins of the Basin and Range province, from northern Nevada and Utah to southern Arizona and New Mexico. With the exception of some minor marine layers in the Salton Trough of southern California, all are continental deposits. Both Pleistocene and Holocene deposits are present but are not separated on the Geologic Map.

The Quaternary deposits generally overlie similar intermontane deposits of Pliocene and Miocene age (Tpc), but these are only partly exposed, and in many basins the Quaternary deposits are the only surface formations. The thickness of the Quaternary is variable and in many areas uncertain. In basins with through-flowing drainage, such as those of the Rio Grande, Gila, and Colorado Rivers, the Quaternary is generally a rather thin set of terrace deposits on top of the much thicker Tertiary, but in other basins it attains considerable thicknesses in its own right. Surface sections of as much as 2,000 feet (600 m) occur in the Salton Trough, and the deposits may attain 3,000 feet (900 m) in subsurface. Thicknesses as great or greater probably occur in the basins with interior drainage in the northern part of the province. Thicknesses in the centers of the basins are uncertain because of

[12]Includes data from Morrison (1965) and Kottlowski, Cooley, and Ruhe (1965).

the difficulty of distinguishing in well records between the Quaternary deposits and the similar underlying Tertiary deposits.

Much of the present topography of the Basin and Range province is a product of Quaternary time, and very little of the late Tertiary topography has persisted. An important part of Basin and Range structure is a product of early Pleistocene block-faulting, which accentuated earlier fault blocks and raised or lowered new fault blocks. Subsequent erosion and deposition has profoundly modified the ranges and basins. Erosional products of the ranges have been carried into the adjacent basins; in basins with exterior drainage, large parts of these erosional products have been carried out of the region, but in basins without outlet they have remained as Quaternary deposits.

A significant result of Quaternary tectonic movements has been the epeirogenic arching of the central part of the Great Basin with respect to its edges, so that even the basin floors in the central part stand 2,000-3,000 feet (600-900 m) higher than those of its east and west sides. As a result, all the present lakes of the region, and to an even greater extent the large Pleistocene lakes, lie close to the east and west sides rather than in the center.

The Quaternary deposits in the closed basins resemble those of the late Tertiary—sloping alluvial fans and bajadas along the edges of the mountains, passing into nearly flat-lying finer-grained alluvium in the centers of the basins, with deposits of ephemeral lakes or playas in the lowest parts. Climatic variations during the Quaternary from arid to sub-humid are reflected in the nature of the successive deposits and the soils formed from them.

During the rainy periods of Pleistocene time, the basins were filled with more permanent water bodies than now exist, the most important of which are those formed during the last, or Wisconsin Glaciation; traces of lacustrine epochs during the earlier glaciations also survive.

The largest and best-known Wisconsin lakes were Lake Bonneville and Lake Lahontan on the east and west sides of the Great Basin, although smaller lakes existed in most of the other closed depressions throughout the Basin and Range province. Lake Bonneville at its maximum covered most of the western half of Utah, had a depth of 1,100 feet (335 m) and an area of 19,940 square miles (51,700 km^2). Lake Lahontan was smaller and more irregular, with many intervening mountain ridges rising above it. It had a maximum depth of 700 feet (213 m) and an area of 8,665 square miles (22,442 km^2). The thickness of the lacustrine deposits produced by these lakes and their predecessors is uncertain, but definitely exceeds 500 feet (150 m).

CENOZOIC VOLCANIC ROCKS

Volcanic rocks of Cenozoic age cover at least a third of the surface of the Western United States, with the greatest areas in the Pacific Northwest (Washington, Oregon, and Idaho), and smaller areas elsewhere (fig. 6). The rocks range in age from Paleocene and Eocene to Quaternary, the most extensive being of Miocene and Pliocene ages.

Classification of the Cenozoic volcanic rocks for purposes of the Geologic Map of the United States presents various problems, some still partly unsolved. Enough is now known, however, to apply a general classification throughout the map area, and to avoid undifferentiated categories such as "Tertiary volcanics (Tv)" and "Quaternary and Tertiary volcanics (QTv)" which have appeared on earlier maps.

The volcanics are divided on the Geologic Map into those of early Tertiary (lTv), Miocene (Tmv), Pliocene (Tpv) and Quaternary (Qv) ages. The early Tertiary volcanics include those of Paleocene, Eocene, and Oligocene ages, and they are generally more deformed and hydrothermally altered than the younger volcanics. Their exact ages are undetermined in many areas, and they crop out in such relatively small areas that it appeared fruitless to attempt a more detailed subdivision. Although the volcanics are mostly not divided according to composition, several exceptions are made. The felsic or rhyolitic volcanics are important in many areas, have somewhat different habits from the rest, and express a significant history. They are mapped separately wherever data are available (lTf, Tmf, Tpf, Qf). The remaining volcanics, indicated by "v," have compositions varying from andesitic to basaltic but include a few undifferentiated felsic volcanics.

In the Coast Ranges of Oregon and Washington, large masses of submarine pillow basalts (Teb) are interbedded in the Eocene stratified sequence. In the Cascade Range to the east, the dominant andesitic eruptives are divisible into lower Tertiary andesites (lTa) of Eocene and Oligocene ages, unconformably overlain by upper Tertiary andesites (uTa) of Miocene and Pliocene ages. The basalts of the Columbia River Group east of the Cascade Range are mapped with the remaining non-felsic Miocene volcanics (Tmv).

Ages of the volcanic rocks can be inferred to some extent by their stratigraphic and structural rela-

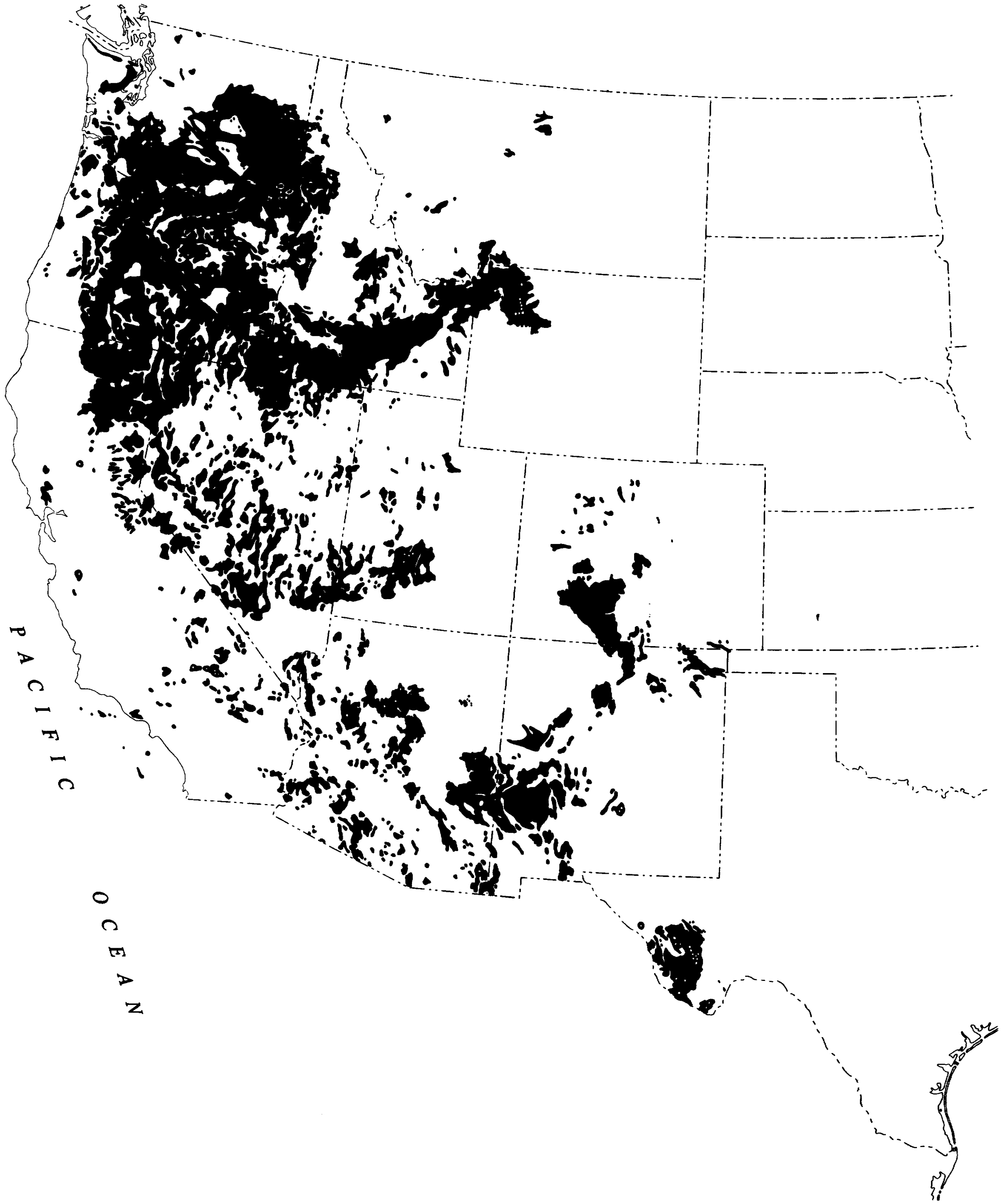

FIGURE 6.—Map of western United States showing distribution of Cenozoic volcanic rocks as represented on Geologic Map of the United States.

tions and are confirmed in part by plant and vertebrate remains in interbedded tuffaceous layers. To an increasing extent, however, ages are being obtained by radiometric dating. Radiometric data are relatively complete in a few areas, but in many others the data are incomplete or lacking. Further radiometric dating will no doubt bring about important revisions of the ages of the volcanics in many areas.

The known ages of the volcanic rocks indicate that the groupings of the volcanics do not correspond neatly to the different Tertiary epochs, so that there are frequently Oligo-Miocene groups, Mio-Pliocene groups, and the like. The age designations by the conventional epochs as shown on the map are thus to some extent unrealistic, and the assignments of the volcanic groups to one epoch or another have had to be arbitrary. Some of these problems are discussed below.

LOWER TERTIARY VOLCANIC ROCKS (lTv)

The lower Tertiary volcanic rocks are largely of Eocene and Oligocene age. Paleocene volcanic rocks are of minor extent and belong to a different cycle of eruption more closely related to the immediately preceding Laramide orogeny. Where present, they are generally included with the Cretaceous volcanics (Kv). The rocks mapped as lower Tertiary volcanics range in age from about 55–25 m.y. Despite the rather lengthy period represented, separation of the Eocene from the Oligocene volcanic rocks is generally not feasible at the present state of knowledge, and many of the sequences in different areas include rocks of both ages.

Lower Tertiary volcanic rocks occur throughout the western United States, but their present areal extent is much less than that of the younger volcanic rocks (fig. 7), due partly to subsequent removal by erosion and to burial beneath younger rocks. Although both Eocene and Oligocene volcanic rocks occur throughout the region, the lower Tertiary volcanic rocks average somewhat older in the north than in the south; north of the 41st parallel Eocene components dominate, farther south Oligocene.

Most of the lower Tertiary volcanic rocks are shown on the Geologic Map as a single unit (lTv). In the Pacific Northwest, however, two categories are shown separately—the Eocene submarine basalts of the Coast Ranges (Teb) and the lower Tertiary andesites of the western part of the Cascade Range (lTa). In addition, the felsic volcanic rocks of the upper part of the lower Tertiary sequence in the San Juan Mountains of southwestern Colorado are indicated separately (lTf).

The general composition of the lower Tertiary volcanic rocks has been summarized as follows (Lipman and others, 1972, p. 220):

> Lower and middle Cenozoic volcanic fields and associated intrusives *** constitute a broad petrologic association of predominantly intermediate compositions. Lavas are typically andesite, dacite, and quartz latite; the common hypabyssal intrusives are granodiorite, monzonite, and quartz monzonite. Somewhat more silicic rocks, especially ash-flow tuffs of quartz latite and low-silica rhyolite that are abundant in some areas, can plausibly be interpreted as high-level differentiates of intermediate-composition magmas. Very mafic and very silicic rocks are much less abundant; in many fields they are sparse or absent. Deviations from this broad outline are most conspicuous at the Pacific and continental interior margins of the Cenozoic volcanic province, where mafic rocks are more abundant.

EOCENE MARINE PILLOW BASALT (Teb)

The Eocene pillow basalts of the Coast Ranges of Oregon and Washington have already been treated in connection with the Eocene sedimentary rocks of that area (p. 10), so they will be mentioned only briefly here. They occur throughout the length of the Coast Ranges, from southwestern Oregon to northwestern Washington, and are interbedded with, or form thick lenses in, the lower and middle Eocene geosynclinal marine sediments; they are less important in the upper Eocene. The basalts are estimated to have a volume of 60,000 cubic miles (250,000 km^3) and were built up in a series of volcanic centers along the axis of the geosynclinal trough, interfingering marginally with the sediments and in places built up to such a thickness that they emerged as islands.

LOWER TERTIARY ANDESITE (lTa)

The Cascade Range, in its 550-mile (890-km) length from northern California, through Oregon, to northern Washington, is a complex accumulation of andesitic volcanics varying in age from early Tertiary through Quaternary. The range is asymmetrical, with a broad, deeply dissected western part that slopes westward to the Puget Trough, the Willamette Valley, and other lowlands, and with a narrower higher part to the east, crowned by a chain of young volcanoes. The western, lower Cascades are formed of a mass of slightly altered and somewhat folded andesitic eruptives, ranging in age from late Eocene, through the Oligocene, into the early Miocene. The High Cascades to the east are built of little dissected andesitic eruptives of

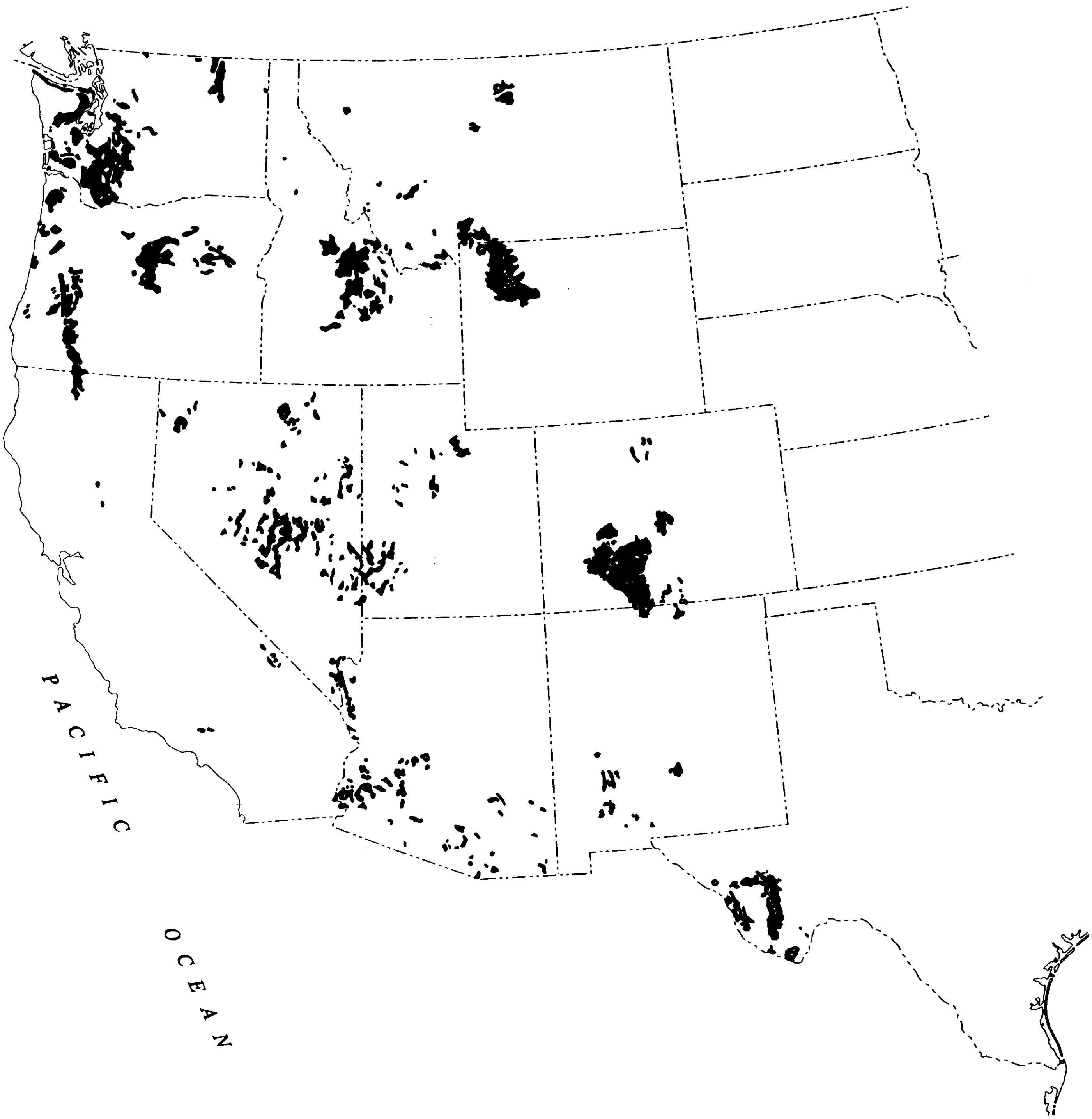

FIGURE 7.—Map of western United States showing distribution of lower Tertiary volcanic rocks as represented on Geologic Map of the United States (units lTv, lTf, lTa, Teb).

Pliocene and Quaternary age.

In Oregon, the great bulk of the western Cascades is formed of the Little Butte Volcanic Series (Peck and others, 1964, p. 11-26), between 5,000 and 10,000 feet (1,500-3,000 m) thick in most places, but in some as much as 15,000 feet (4,500 m). On the west it lies in places on the upper Eocene Colestin Formation, a continental deposit with its own volcanic components (Tec), and elsewhere on the pre-Tertiary basement. Northwestward, the Little Butte Series intertongues with marine tuff and sandstone of Oligocene and early Miocene age. Toward the north it is overlain by the middle Miocene Columbia River basalt (Tmv) and toward the east by the upper Tertiary andesites of the High Cascades (uTa).

The Little Butte Series (lTa) is formed of massive beds of andesitic and dacitic tuff, deposited by ashflows, and interbedded flows and breccias of olivine basalt, and of bedded tuff, welded tuff, and flows of dacite and rhyodacite. In some segments, pyroclastic and volcaniclastic rocks make up as much as three-quarters of the sequence and are shown separately on the Geologic Map as continental deposits (Toc). The rocks were erupted from chains of volcanic vents, of which at least 30 have been identified. Most of the volcanic rocks are partly or completely altered by low-grade (zeolite facies) metamorphism, and they have been altered to hornfels near intrusives.

Fossil plants of middle to late Oligocene and early Miocene age occur at many levels and localities in the Little Butte Volcanic Series. The upper Oligocene floras are like those in the John Day Formation farther east in Oregon. The older floras indicate a tropical or subtropical climate, and the youngest a somewhat cooler climate.

The lower Tertiary andesites extend about 45 miles (72 km) southward into California to the latitude of Mount Shasta, beyond which they are overstepped by the younger Cenozoic volcanics (Macdonald, 1966, p. 69-70). The California sequence has about the same thickness as in Oregon; the rocks are generally less altered because of lack of intrusives. There are some units as much as 1,000 feet (300 m) thick of coarse andesitic tuff-breccia, containing angular blocks which reach 4 feet (1.2 m) across.

In northern Oregon the lower Tertiary andesites are covered by younger volcanics for about 50 miles (80 km) toward the Columbia River, but they reappear in southern Washington, west of Mount St. Helens and Mount Rainier, where they form the Ohanapecosh Formation, named for typical exposures in Mount Rainier National Park (Fiske and others, 1963, p. 4-20). Exposed sections of the formation are as much as 10,000 feet (3,000 m) thick, and the total may exceed 15,000 feet (4,500 m). The Ohanapecosh consists of volcaniclastic rocks and basaltic andesite lava. Lava flows and coarse volcaniclastic rocks form thick local accumulations that grade laterally into finer grained clastic rocks. Ash-flow tuffs and rhyolites are a very minor constituent. Large parts of the formation were laid down under water, probably in lakes and coastal lagoons. The clastic rocks contain fossil plants of middle and upper Eocene age at some localities; the highest unfossiliferous part of the unit may extend into the Oligocene.

In Washington, the boundary between the lower and upper Tertiary andesites of the Cascade Range is placed on the Geologic Map at the unconformable contact between the Ohanapecosh and Stevens Ridge Formations on the advice of C. A. Hopson (written commun. 1972). The Stevens Ridge is of upper Oligocene and Miocene age, so that the mapped boundary is at a lower level than that in Oregon.

Westward in the Washington Cascades, the andesitic components fade out and intertongue with continental deposits, such as the coal-bearing upper Eocene Cowlitz Formation of the Centralia-Chehalis district. The underlying Northcroft Formation is largely andesitic, but its lower part is sedimentary and contains basaltic detritus derived from the west. The upper Eocene formations of this area lie on the east edge of the lower and middle Eocene pillow basalts of the Coast Ranges to the west.

CLARNO FORMATION (lTv) OF NORTHEASTERN OREGON

East of the Cascade Range, the next extensive body of lower Tertiary volcanic rocks is in the northern and western parts of the Blue Mountains uplift, the Clarno and John Day Formations. The John Day is more dominantly volcaniclastic than the Clarno, is shown as Oligocene continental deposits (Toc) on the Geologic Map, and is described under an earlier heading (p. 20).

The Clarno, lying unconformably beneath the John Day and unconformably on the pre-Tertiary basement rocks of the Blue Mountains uplift, is more than 5,000 feet (1,500 m) thick. It is composed of basaltic, andesitic, and rhyolitic flows, breccia, tuff, and volcanic conglomerate, with thick lenses of of fine-grained water-laid ash; thick flows of hornblende-bearing porphyritic andesite and dacite, and associated breccia occur locally. Silicified wood is common in the volcanic breccia, and leaf impressions are abundant in some of the silty beds. Vertebrate remains are rare or absent. The floras are lower to upper Eocene in age, and the highest are perhaps Oligocene. Radiometric ages of 41 to 34 m.y. (Eocene and Oligocene) are reported from the Clarno.

CHALLIS VOLCANICS (ITv) OF SOUTH-CENTRAL IDAHO

In south-central Idaho east of the Idaho batholith, the early Tertiary Challis Volcanics overlie Paleozoic rocks (Ross, 1962, p. 73-102). They cover an area of 3,000 square miles (8,000 km^2); they were originally even more extensive but have now been fragmented by deformation and erosion. For the most part they were spread out on a nearly level erosion surface of the Paleozoic rocks, but some higher peaks projected, adjoined by bouldery basal conglomerate. The Challis Volcanics were originally more extensive to the south, across the site of the Snake River Plain, and the remnants of lower Tertiary volcanics in the ranges of northernmost Nevada are probably their former extensions; the intervening downwarp and rift of the Snake River Plain, thickly filled by younger volcanics, did not begin to develop until the Miocene.

The Challis Volcanics are 2,500 to more than 5,000 feet (750-1,500 m) thick. Subdivisions can be recognized in most areas. The thickest and most persistent unit is the latite-andesite member at the base. Above this member are flows of basalt and calcic andesite, commonly interbedded with tuff, the most conspicuous of which are in the Germer Tuffaceous Member in the upper part.

In the northwest part of the volcanic area, a more altered phase of the lavas was formerly distinguished as the Casto volcanics, thought to be of Permo-Triassic age, but it is now interpreted to be an altered phase of the Challis, produced in proximity to the large early Tertiary granodiorite pluton in that area; only one volcanic unit is thus present.

The Challis Volcanics contain fossil plants at many localities and levels, assigned to the Eocene and to the Oligocene by various paleobotanists. A few vertebrate remains, reported to be of Miocene age, occur. Lead/alpha determinations on intrusives in the Challis Volcanics yield Eocene ages of 40 to 50 m.y.

The floras are a product of a sub-alpine conifer forest that lived at an altitude of about 4,000 feet (1,200 m), which indicates the existence of a highland along the central axis of the Cordillera, between lower country to the east and west (Axelrod, 1968). As a result of later deformation, the early Tertiary volcanics north of the Snake River Plain have been raised 5,000 feet (1,500 m) higher, to altitudes of 10,000 feet (3,000 m) or more.

WESTERN MONTANA

Many small areas of lower Tertiary volcanics occur in western Montana, both within the Rocky Mountains and in outlying mountain groups in the Great Plains to the east. They are probably remnants of formerly more extensive volcanic fields, now much reduced by erosion, whose extent is suggested by the even wider scatter of early Tertiary hypabyssal intrusions, especially in the region east of the Rocky Mountains.

One of the larger bodies of the lower Tertiary volcanics of western Montana is the Lowland Creek Volcanics on the western flank of the Boulder batholith near Butte (Smedes, 1962), which covers an area of 800 square miles (2,000 km^2) and has a thickness of nearly 6,000 feet (1,800 m). The volcanics lie on an eroded surface with 1,000-2,000 feet (300-600 m) of relief cut on the Boulder batholith and the associated Elkhorn Mountain Volcanics. The Lowland Creek is a sequence of quartz latitic volcanic rocks, divisible into as many as six units, each separated by unconformities, some of which involved block-faulting and other deformation. The units include ash-flow sheets, volcanic breccias, quartz latite lava, and quartz latite vitrophyre, and they are cut by many small contemporaneous intrusives. The lower part contains a few non-diagnostic plants (once thought to be of Oligocene age) and has yielded early Eocene K/Ar ages of 48-50 m.y.

East of the Rocky Mountains intrusives occur in the Crazy Mountains, Castle Mountains, Little Belt Mountains, Highwood Mountains, Bearpaw Mountains, Little Rocky Mountains, and Sweetgrass Hills. These are mostly near-surface stocks and laccoliths, and in some of the areas, notably the Highwood and Bearpaw Mountains, effusive equivalents are preserved. The igneous rocks range in composition from ordinary rhyolites, andesites, and syenites, to strongly alkalic rocks rich in potash and soda (Larsen, 1940). The igneous rocks east of the Rocky Mountains are generally credited to be of Eocene age.

ABSAROKA VOLCANIC FIELD, WYOMING AND MONTANA

One of the major lower Tertiary volcanic areas in the western United States is the Absaroka volcanic field in northwestern Wyoming and southern Montana, which forms the high, deeply dissected volcanic plateau of the Absaroka Mountains with a northwestward extension into the Gallatin Range. The volcanic rocks, called the Absaroka Volcanic Supergroup (Smedes and Proskta, 1972), have an area of 10,000 square miles (2,500 km^2), and a volume of 7,000 cubic miles (29,000 km^3). The volcanic area extends southeastward for 160 miles (250 km), with a width of as much as 60 miles (95 km). Toward the southwest, the deeply eroded surface of the Absaroka rocks is overlapped by the younger volcanics of Yellowstone National Park, and toward the northeast they border the Precambrian massif of the Beartooth Mountains, which probably formed a barrier to the eruptions. Eastward and southeastward the volcanics rise in imposing erosional escarpments that overlook the Bighorn and Wind River basins, and the volcanics were originally more extensive in these directions. Thicknesses of the volcanic rocks in continuous sections are as much as 6,500 feet (2,000 m), and the total composite thickness probably exceeds 12,000 feet (3,650 m).

The Absaroka volcanic rocks are principally calc-alkalic andesite, with some dacite flows and breccias and minor potassic lavas of the shonkinite suite. In the area east of Yellowstone Park, the volcanics fall into two groups, each with a lower acid breccia, a middle basic breccia, and an upper set of basalt sheets (Rouse, 1937). These have traditionally been called the early acid breccia, early basic breccia, early basalt sheets, late acid breccia, late basic breccia, and late basalt sheets. Later, the units of the sequence were formally named (Smedes and Proskta, 1972, p. 10-11); the early acid breccia is the Washburn Group, the early basic breccia and basalt sheets are the Sunlight Group, and the late acid breccia, late basic breccia, and the late basalt sheets are the Thorofare Creek Group. The acid breccias are light colored and consist of hornblende andesite and hornblende-mica andesite. The basic breccias are dark-colored, owing to their higher content of ferro-magnesian minerals.

The Washburn Group constitutes much of the sequence in the Gallatin Range, but farther southeast it has a patchy distribution owing to the irregular surface on which it was laid and to erosion of its top, so that it is no more than 1,000 feet (300 m) thick. The early basic breccia of the Sunlight Group is much more prominent, more widely distributed, and thicker, reaching 5,000 feet (1,700 m) near the eruptive centers. It is a complex of agglomerates, volcanic conglomerates, tuffs, and mudflows. The early basalt sheets, which average 1,000 feet (300 m) thick, occur throughout the eruptive field. The late acid breccia of the Thorofare Creek Group is as much as 2,500 feet (760 m) thick, and the late basic breccia as much as 2,500 feet (825 m). The late basalt sheets are preserved only as remnants on the high divides.

In the Gallatin Range to the northwest, where the rocks are mostly Washburn Group, flows dominate over breccias (Chadwick, 1970), but at the southeast end of the field in Wyoming, the sequence in the Thorofare Creek Group is dominantly sedimentary and volcaniclastic (Love, 1939, p. 73-85). Here, the group is represented by the Tepee Trail Formation and Wiggins Formation.

The Absaroka volcanics were erupted from a series of centers extending northwestward through the field. The centers lie in two belts which are 15 miles (25 km) apart in the Gallatin Range and diverge southeastward to 35 miles (55 km) in the Absaroka Mountains. The vent areas were composite stratovolcanoes and shield volcanoes composed of flow breccias, lava flows, mudflows, and avalanche debris, with steep primary radial dips; the vents were intruded by stocks, plugs, laccoliths, and radial swarms of dikes. Away from the vents, the rocks pass into low-dipping volcanic conglomerate and breccia, volcanic sandstone, and siltstone, and air-fall tuff.

The Absaroka volcanic rocks lie stratigraphically over the non-volcanic early Eocene Wasatchian beds in the nearby Bighorn and Wind River basins, but they are themselves early Tertiary. They contain abundant plant remains and some vertebrate fossils and have been dated radiometrically. This evidence indicates that the Washburn Group is late Wasatchian and early Bridgerian in age, and that the Sunlight and Thorofare Creek Groups are of Bridgerian and Uintan age. Earlier interpretations that the upper part of the Absaroka sequence extends into the Oligocene have now been disproved.

Genetically related to the volcanic activity is the Heart Mountain detachment thrust in the Paleozoic rocks beneath the volcanics along the northeast side of the Absaroka Range (Pierce, 1957). Here, Ordovician to Mississippian carbonates have become detached from the underlying Cambrian strata and have moved southeastward, probably by gravity sliding; on the east edge of the mountains they ride up and over the Wasatch Formation, with remnants of the carbonate rocks overlying the Wasatch in Heart Mountain and McCulloch Peaks well out in the Bighorn Basin. The upper carbonates have moved independently as detached blocks, leaving voids that were filled by the early basic breccia at the base of the Sunlight Group. Movement of the blocks may have been nearly contemporaneous with the eruptions of the Washburn Group, which is scantily preserved in the area. The gravity sliding was somehow triggered by the volcanism in the Absaroka volcanic field.

EASTERN GREAT BASIN

Lower Tertiary volcanic rocks (lTv), mostly Oligocene, form the lower part of the Tertiary sequence in many of the ranges in the eastern part of the Great Basin, in southwestern Utah and east-central Nevada (figs. 8, 9). The volcanics are of several contrasting compositions as indicated below, but they are not differentiated on the map. In many places the lower Tertiary volcanics lie on an erosion surface cut on the Mesozoic and older rocks, but in others thin units of older Tertiary continental deposits intervene. The lower Tertiary volcanics wedge out westward and southward, so that younger Tertiary volcanics lie directly on the pre-Tertiary rocks. Eastward, however, they extend beyond the edge of the Colorado Plateau.

In the western part of the region, the lower Tertiary volcanics are lavas of intermediate composition, mostly andesite and dacite, with a thickness of about 1,000 feet (300 m). Their extrusion began abruptly about 39 m.y. ago and ceased at about 34 m.y. ago (McKee and Silberman, 1970, p. 2326). Eastward, these lavas give place to and are overlain by felsic volcanics.

The felsic volcanics are mainly rhyolitic ash-flow tuffs or ignimbrites, which were spread as broad sheets over a nearly level surface for thousands of square miles. Successive flows thus form a recognizable stratigraphic sequence that can be traced and correlated from one mountain range to another. Eruption of the felsic volcanics began about 34 m.y. ago and continued from the Oligocene into the Miocene.

In the Iron Springs district of southwestern Utah the basal ash-flow tuff sequence, or Needles Range Formation, lies on the non-volcanic Claron Formation (Txc of Geologic Map) (Mackin, 1960, p. 99-100; Anderson and Rowley, 1975, p. 10-13). The Claron, about 1,500 feet (450 m) thick, is a continental deposit of clastics and interbedded limestone. It is lithically similar to and probably equivalent to the so-called "Wasatch Formation" at the south end of the High Plateaus of Utah to the east, which is of Paleocene and Eocene (Flagstaff and Green River) age. The age of the Claron itself is undetermined, but it probably includes Paleocene and Eocene. The Needles Range Formation, which lies on it conformably and interfingers with it laterally, has a radiometric age of 29-28 m.y. (Oligocene). It consists of two to five flows that are recognizable over an area of about 13,000 square miles (33,000 km^2) in Utah and Nevada. To the west, the Needles Range is underlain by two other ash-flow units, the Stone Cabin and Windous Butte Formations, probably equivalent to the upper part of the Claron and 32 m.y. or more old (Cook, 1965, p. 12-16). Above the Needles Range are other ash-flow units, one of which, the Isom Formation, has an age of about 25 m.y., or late Oligocene. The higher ash-flow units of the Great Basin, of Miocene and later ages, are discussed under a later heading.

SAN JUAN VOLCANIC FIELD, SOUTHWESTERN COLORADO

The San Juan Mountains of southwestern Colorado are a lofty, deeply dissected volcanic plateau with an area of about 9,700 square miles (25,000 km^2). After discovery of precious metals in the mountains in the 1870's, the region was investigated by many geologists, especially by the staff of the U.S. Geological Survey who produced a set of geologic folios. The results were summarized in a classic report by Larsen and Cross (1956). Much new work has been done in the last few decades, resulting in many revisions and reinterpretations; for a summary, see especially Lipman, Steven and Mehnert (1970).

The San Juan volcanic field developed over the Uncompahgre-San Luis geanticline, an intermittently positive axis that was raised during late Paleozoic time, and again in Late Cretaceous and Paleocene time as a part of the Laramide orogeny. During the Laramide orogeny, andesitic volcanism occurred along the axis. Although most of the andesitic rocks were eroded, their detritus occurs in the Paleocene and Eocene deposits of the San Juan basin. During the late Eocene, the eroded surface of the Precambrian along the axis was covered by the thin, non-volcanic Telluride and Blanco Basin Formations; the main period of volcanism was later.

Initial eruptions from numerous volcanoes produced voluminous intermediate lavas and breccias (lTv), mostly of alkali andesite, rhyodacite, and mafic quartz latite that make up the San Juan, Lake Fork, and Conejos Formation. The early volcanics blanketed most of the field and have a volume of more than 10,000 cubic miles (40,000 km^3) (fig. 10). These eruptions occurred between 35 and 40 m.y. ago, or during the early Oligocene.

The intermediate volcanics are overlain by great

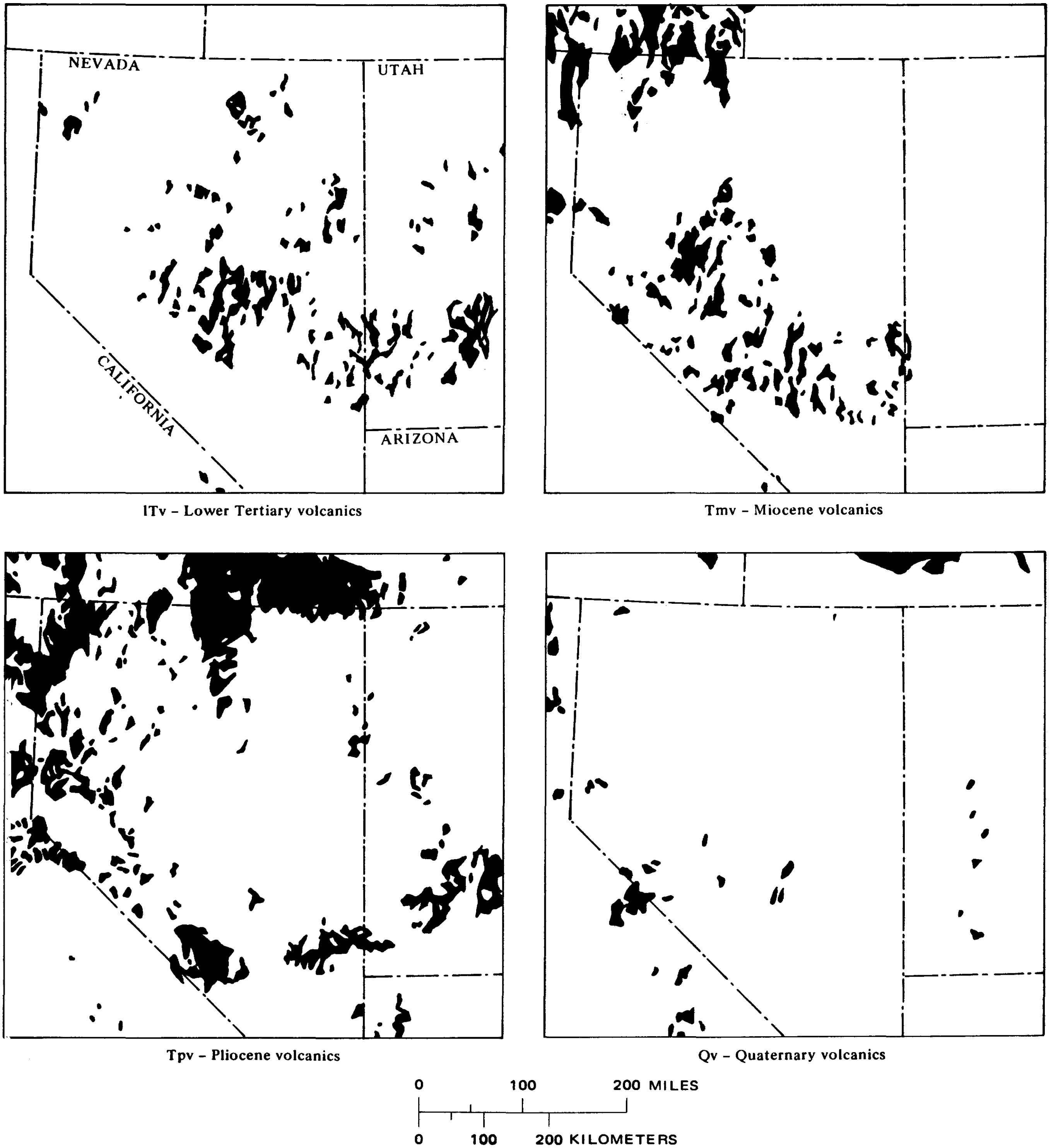

FIGURE 8.—Maps of Great Basin in Nevada and adjacent States showing distribution of volcanic rocks of successive Cenozoic ages as represented on Geologic Map of the United States. Notice the apparent outward progression through time of volcanic activity from a center in east-central Nevada and adjacent Utah.

sheets of quartz latite and low-silica rhyolite ash-flow tuffs (lTf). More than 15 separate sheets derived from calderas in the western and central San Juan Mountains have been recognized. The ash-flow eruptions all occurred within 5 m.y., between 30 and 25 m.y. ago. Although areally extensive, their volume is only about half that of the older intermediate lavas. Four of the largest cal-

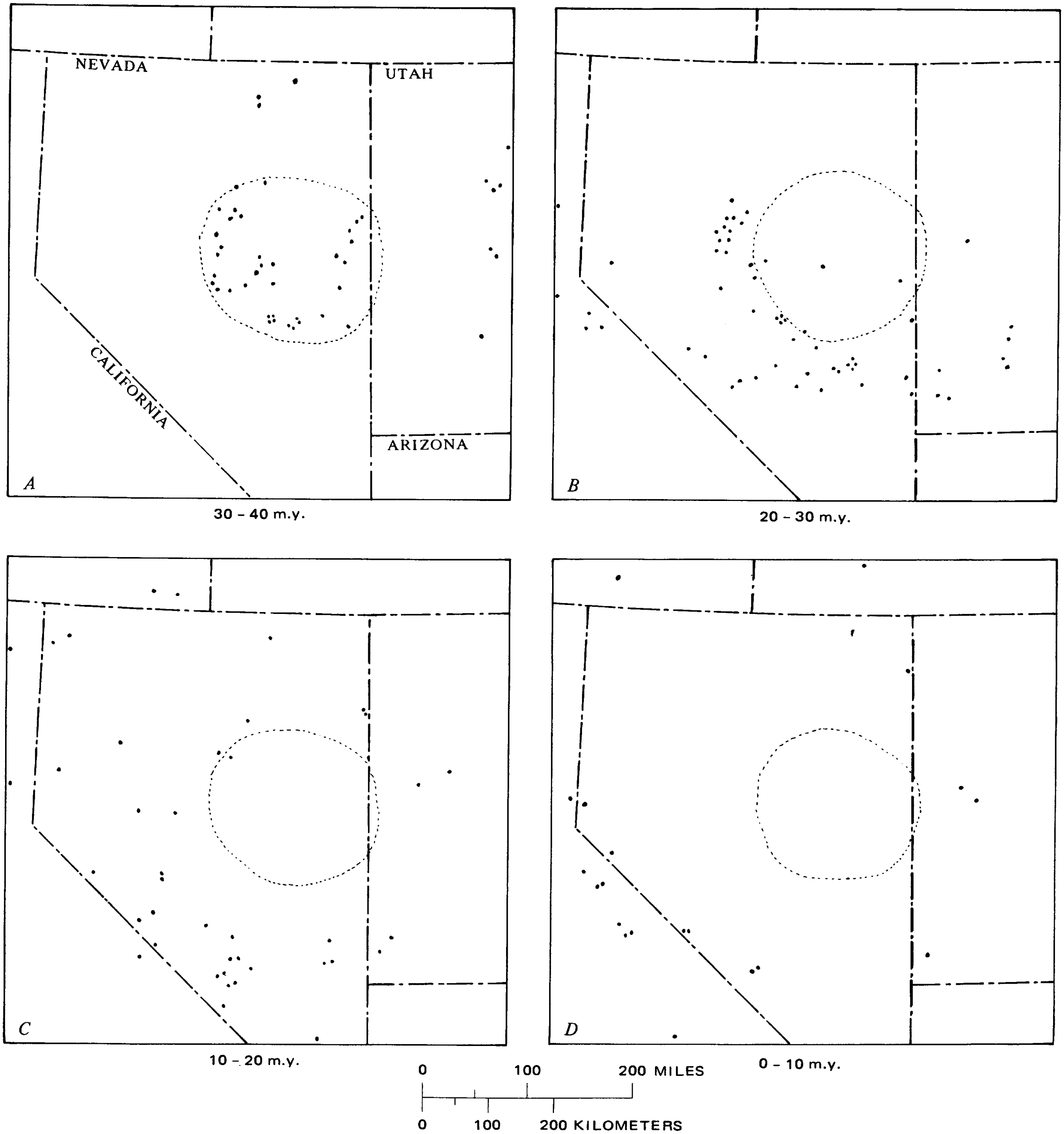

FIGURE 9.—Maps of Great Basin in Nevada and adjacent States showing the distribution of radiometric dates on felsic volcanic rocks of successive ages and illustrating the same outward progression of activity shown in figure 8. Original "core" area is outlined by dotted line. Note that the units used here are not exactly comparable to those of figure 8 but represent arbitrary 10 my intervals. (After Armstrong and others, 1969.)

deras are shown on the Geologic Map but there are many others (fig. 10). Those in the western part of the field formed the San Juan volcanic depression about 25 miles (40 km) long, in which are nested the Silverton and Lake City calderas. Those in the central part formed a cauldron complex 50 miles (80 km) long and 15-25 miles (25-40 km) wide, containing six or more partly coalesced calderas.

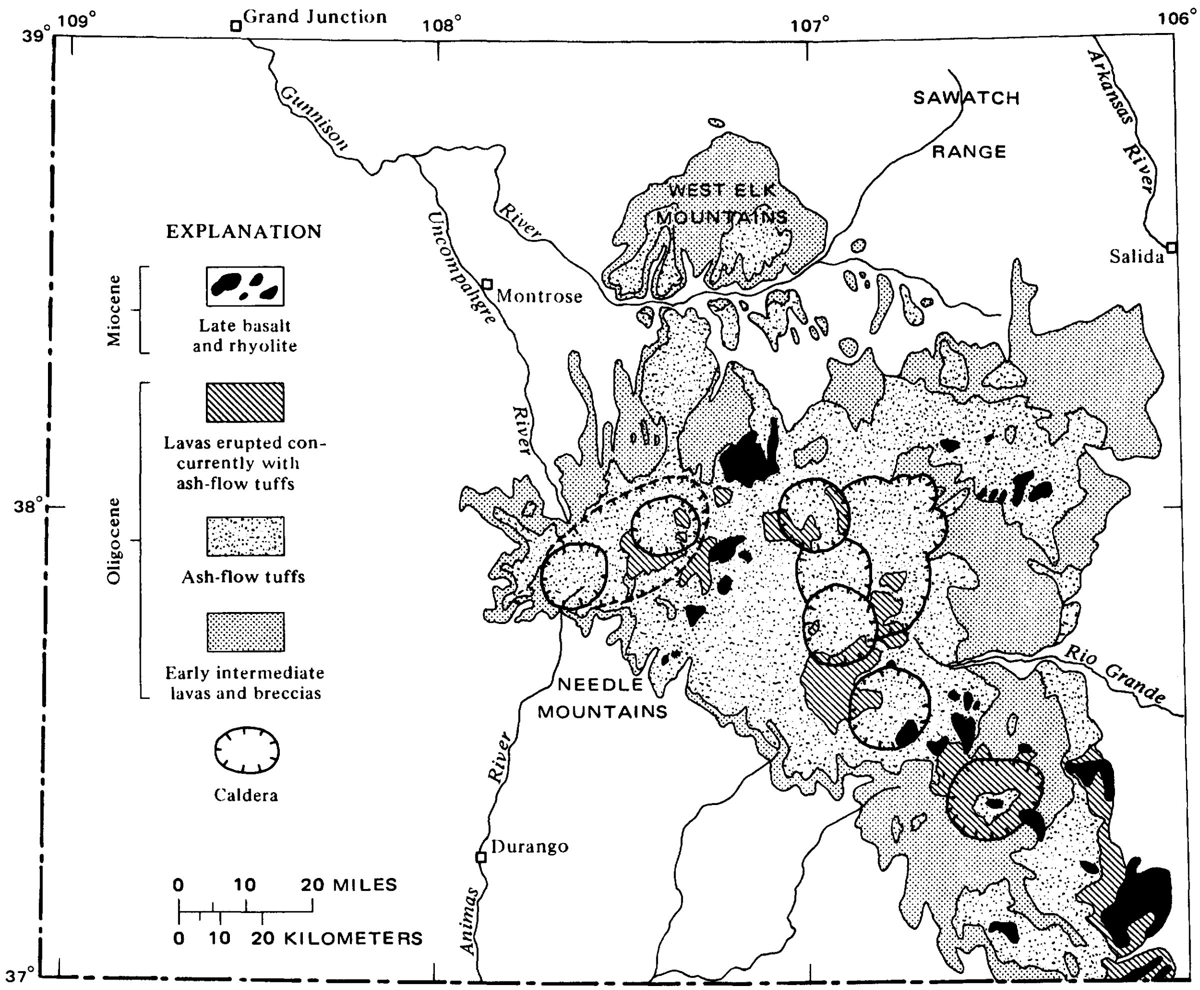

FIGURE 10.—Map of lower and middle Tertiary volcanic rocks in San Juan Mountains area, southwestern Colorado, showing distribution of principal units and calderas (after Lipman and others, 1970).

The ash-flow sequence is interbedded with and overlain by intermediate to silicic lava flows and breccias, the youngest of which is the Fisher Quartz Latite, erupted about 25 m.y. ago (near the end of the Oligocene).

Minor eruptions, which continued into the Miocene are represented by erosional remnants on the crests of the mountains. These, and the Pliocene volcanics of nearby areas, are discussed under later headings.

The San Juan volcanic field was originally much more extensive than its present limits. An outlier with a nearly identical volcanic sequence occurs in the West Elk Mountains north of the canyon of the Gunnison River. The spread of the volcanics was limited on the northeast by the uplift of the Sawatch Mountains, and partially on the southeast side by the Precambrian massif of the Needle Mountains. To the northwest, west, and southwest, the volcanics spread widely. Hints as to their former extent are afforded by congeneric intrusions in the Mesozoic and older rocks. Eastward, the field is covered by later Tertiary deposits (Tpc) in the downwarp of the San Luis Valley, but its edge probably coalesced with the Oligocene volcanic fields of the southern Front Range and Wet Mountains (see below).

OTHER AREAS OF LOWER TERTIARY VOLCANICS IN SOUTHERN ROCKY MOUNTAINS

The San Juan volcanic field is the largest of many areas of lower Tertiary volcanics in the Southern Rocky Mountains of Colorado. At the close of the early Tertiary eruptions, lava flows and volcaniclastic sediments probably blanketed most of the present mountainous areas south of the central Front Range. There were outlying volcanic areas to the north, in the Never Summer Mountains of the northern Front Range and the Rabbit Ears Range between North and South Parks (Steven, 1975).

The largest of the outlying areas is the Thirty-nine Mile field in the southern Front Range (Epis and Chapin, 1968) with an area of 1,500 square miles (3,900 km^2). The field was spread over an erosion surface of low relief cut on Precambrian rocks in Eocene time following the Laramide orogeny. Initial eruptions from a cauldron in the northern part of the field were andesite flows and breccias with a late Eocene age of 40 m.y., or somewhat earlier than the first eruptions in the San Juan field to the west. Later eruptions from centers farther south first produced andesite flows and pyroclastics, followed by silicic ash-flow tuffs with an early Oligocene age of about 34 m.y. They were spread northeastward into a lake dammed by the eruptions in which the Florissant Lake Beds accumulated. Minor andesitic eruptions continued into the Miocene, from which 19 m.y. dates have been obtained.

A smaller area of lower Tertiary volcanics occurs in the Silver Cliff and Rosita Hills districts on the west slope of the Wet Mountains to the south. Eruptions were from local cauldrons, and as in the other fields, include both andesite flows and rhyolitic ash-flow tuffs. The oldest are 40 m.y. old (late Eocene), but the bulk of the volcanics is Oligocene, with ages of 38–33 m.y.

Extensive andesitic eruptions in the Mineral Belt of the central Front Range during the Laramide orogeny contributed large quantities of andesitic debris to the Late Cretaceous and Paleocene formations in the Denver and North Park basins to the east and west, but few outcrops of the andesite remain in the source areas. Volcanism was renewed during the Oligocene, but except for a few remnants of flows, most indications of the event are in the associated intrusives, which were formerly confused with the Laramide intrusives (Kg3) that occur in the same area. The large Mount Princeton pluton in the Sawatch Range to the west has been dated radiometrically as late Eocene or early Oligocene and probably was the root of a volcanic center of that time whose surface rocks have been eroded.

The lower Tertiary volcanic fields of the Southern Rocky Mountains may have formed over a large subjacent batholith or chain of batholiths (Steven, 1975, p. 88-91). A series of pronounced gravity lows extending northeastward from the San Juan Mountains to the Mineral Belt of the central Front Range is probably a geophysical expression of the batholith.

SOUTHWESTERN ARIZONA

Lower Tertiary volcanic rocks (lTv) are shown on the Geologic Map in many of the desert ranges of southwestern Arizona, along with the more prevalent Miocene and Pliocene volcanics (Tmv, Tpv). The older volcanics of the region were classed on the Geologic Map of Arizona (1969) as Cretaceous (Kv). Cretaceous volcanics occur farther east in the State, where they intertongue with fossiliferous strata; those farther west were assigned a Cretaceous age on the tenuous assumption that they were involved in the Laramide orogeny, but most of them are certainly Tertiary, as shown by radiometric dating at various localities.

The rocks shown as lower Tertiary volcanics are generally more deformed and altered and less fresh-appearing than those of younger ages, and in many places they are separated by angular unconformities, but they are probably of diverse ages.

In northwestern Arizona south of Boulder Dam, a 17,000-foot (5,200 m) sequence of Tertiary volcanics overlying the Precambrian basement is divided into the Patsy Mine, Golden Door, and Mount Davis Volcanics (Longwell, 1963, p. 18–29); the lower part of these is represented as lower Tertiary volcanics on the Geologic Map. The Patsy Mine Volcanics are a plausible candidate for lower Tertiary, because they are more deformed and altered than the higher units. However, radiometric determinations give little comfort to the notion. Radiometric ages determined on the Patsy Mine are between 14 and 18 m.y. (Miocene), except for a doubtful 40 m.y. date in the lower part (Anderson and others, 1972, p. 275). To the west in the Mojave Desert region of California, no volcanics older than Miocene are known.

Much farther southeast, in the Tucson Mountains west of Tucson, the lowermost volcanic unit (Cat Mountain Rhyolite), shown as lower Tertiary on the Geologic Map, has yielded Cretaceous ages of 65–70 m.y. (Bikerman and Damon, 1966, p. 1228).

In the intervening area, the designation of lower Tertiary for the older volcanics is generally more appropriate, as Oligocene dates of 26–29 m.y. have been reported from a number of localities, as in the Sierrita Mountains and the Yuma area. Compositions range from andesite to rhyolite.

MOGOLLON PLATEAU, SOUTHWESTERN NEW MEXICO

The Mogollon Plateau is a volcanic field covering more than 20,000 square miles (50,000 km^2) at the southeast corner of the Colorado Plateau in southwestern New Mexico and adjacent Arizona. On the Geologic Map its rocks are shown as Miocene and Pliocene volcanics (Tmv, Tpv), with minor areas of lower Tertiary volcanics (lTv) along the southeast edge. This representation was based on an interpretation of units shown on the Geologic Maps of New Mexico (1965) and Arizona (1968). On the New

Mexico map, the older volcanics are classed as Datil Formation (Td), divided into various lithologic facies, and on the Arizona map as "intermediate volcanic rocks" (Tvi); these were assigned a Miocene age, following prevailing opinion. The younger basaltic rocks are shown on both maps as QTb; these were assigned a Pliocene age.

Further studies of the field were in progress at the time of map compilation and suggested important revisions of age assignments, but specific details did not become available until the Geologic Map was in press. The new data, supported by radiometric determinations, indicate that in general the rocks designated as Miocene on the Geologic Map are actually Oligocene (lTv), and those designated as Pliocene are actually Miocene (Tmv) (fig. 11) (Elston and others, 1973; Elston and others, 1976).

The volcanic rocks of the Mogollon field comprise three overlapping magma suites: (a) an early calc-alkalic andesite to rhyolite suite with ages of about 29-43 m.y.; a high-silica alkali rhyolite suite with ages of about 21-31 m.y.; and (c) a basaltic suite, contemporaneous with the other two suites, but continuing from about 37 m.y. to the present, but reaching its peak during and just after the high-silica alkali rhyolite eruptions. The volcanic rocks of the Mogollon field evolved in a single direction, and not in cycles. Calc-alkalic rocks appeared early and then faded out, becoming scarcer just as the high-silica alkali rhyolite became abundant; basaltic andesite and basalt occur at many stratigraphic levels.

The rocks of the rhyolite suite are believed to have originated in a large subjacent batholith. They were erupted from a series of cauldrons and volcanic-tectonic depressions, mostly confined to the Mogollon Plateau, some more than 35 miles (55 km) in diameter. They are bordered by broad ring-fracture zones. Within the cauldrons ash-flow tuffs exceed 3,000 feet (1,000 m) in thickness, but they thin in the outflow sheets. Ring-fracture zones are characterized by domes and flows of flow-banded rhyolite associated with moat and flank deposits of bedded pumice. Lower temperature pumice leaked out along ring fractures and filled moats around resurgent domes. Lake beds, landslide blocks, and conglomerate beds are common in the moats.

During the main period of eruption, the region was tectonically quiet. Following the eruptions, Basin and Range structure, produced by regional tension, began to develop about 21 m.y. ago, but the block-faulting thereby created was confined to the periphery of the plateau. Basalts are interbedded in the lower part of the Gila Formation that was deposited in the block-faulted depressions. Very little of these later basalts was erupted within the plateau itself.

TRANS-PECOS TEXAS

In the southwestern part of the trans-Pecos region of west Texas, 240 miles (380 km) southeast of the Mogollon field, a broad lower Tertiary volcanic field extends southwestward across the Rio Grande into Mexico. The volcanic field includes the Davis Mountains on the northeast, extends westward into the Sierra Vieja or Rim Rock area, and southward into the Chisos Mountains of the Big Bend area. Large parts of the field have been studied in recent decades, mostly by the staff of the Bureau of Economic Geology and by students of the University of Texas, the results of which have been summarized and correlated by Maxwell and Dietrich (1970). A notable feature of the volcanic rocks is their high alkalic content, which is especially evident in the associated intrusions.

The volcanic rocks were erupted onto an irregular erosion surface of Cretaceous and Paleozoic rocks, from several centers, each providing a succession of volcanic and volcaniclastic units, having a wide variety of local names. These sequences have been correlated by widespread layers of ash-flow tuff, of which the Mitchell Mesa or Brite Tuffs are most persistent, and have been used as a base-line for correlation by Maxwell and Dietrich (1970, pl. 1). On the Geologic Map this base-line has been adopted for separating lower Tertiary volcanics (lTv) from Miocene volcanics (Tmv). Although this separation is convenient for map purposes, it is misleading as to age, for the rocks below the base-line are mainly Eocene, and those above it mainly Oligocene.

The oldest Tertiary rocks in the trans-Pecos region are in the Big Bend area surrounding the Chisos Mountains. Here, most of the former extent of the volcanics has been eroded, leaving only remnants in the higher mountains. Congeneric intrusive stocks abound in the Cretaceous of the surrounding lower country. East of the Chisos Mountains the Cretaceous rocks are succeeded by the nonvolcanic Black Peaks, Hannold Hill, and Canoe Formations, which contain Paleocene, lower Eocene, and middle Eocene vertebrates, respectively. Thin basalt flows occur in the Canoe Formation, but the main volcanic sequence consists of the conformably overlying Chisos and South Rim Formations, totaling 3,600 feet (1,100 m) thick. The Chisos is mainly volcaniclastic, but it includes widely traceable basalt members; the South Rim is massive rhyolite flows and associated flow-breccia. A few late Eocene mammals occur in the lower part of the Chisos

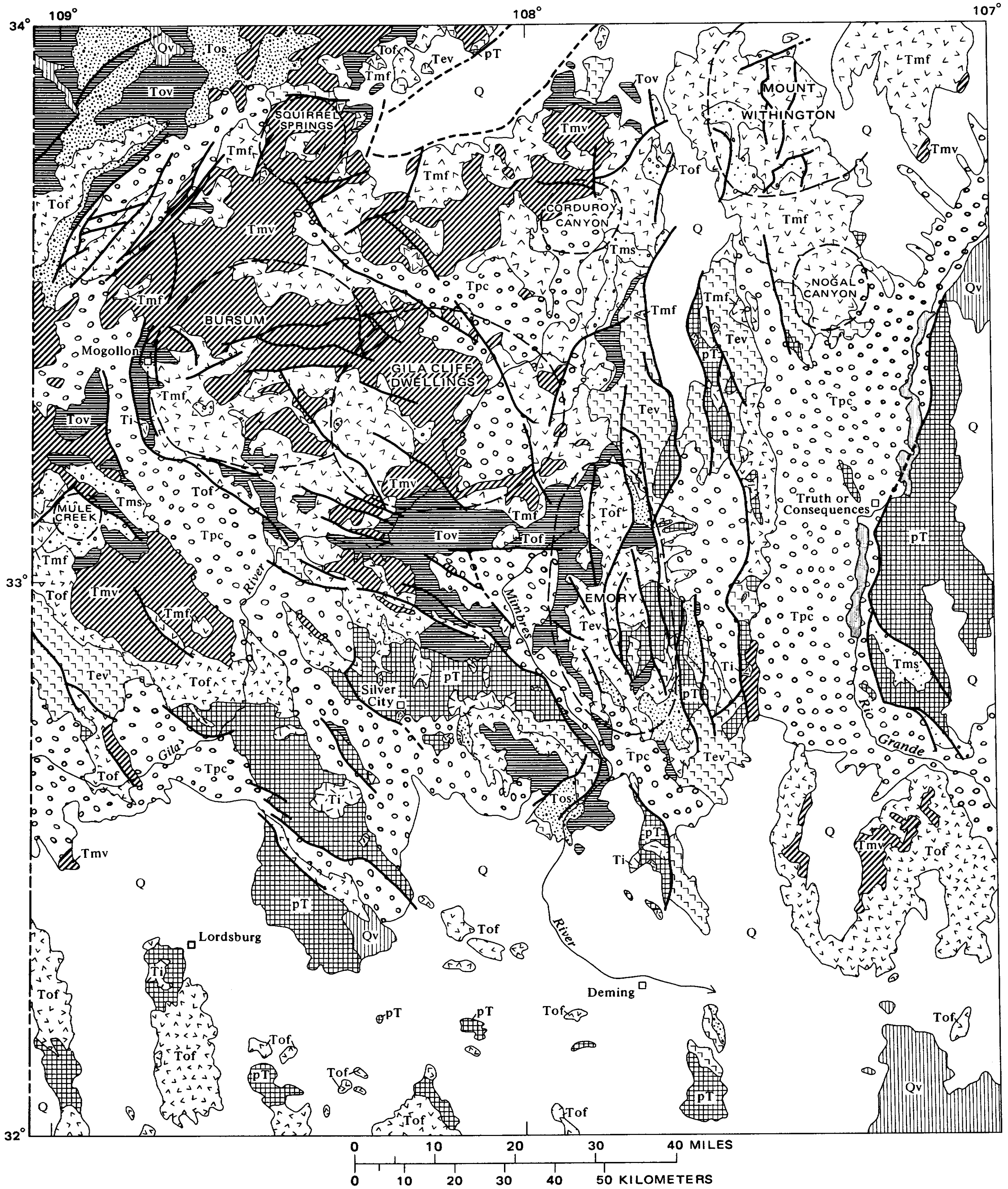

FIGURE 11.—Map of Mogollon Plateau and vicinity, southwestern New Mexico showing distribution of the Cenozoic volcanic units and calderas. The representation is a recent revision and differs in important respects from than on Geologic Map of the United States. (Compiled from Elston and others, 1976, supplemented by Geologic Map of New Mexico, 1965).

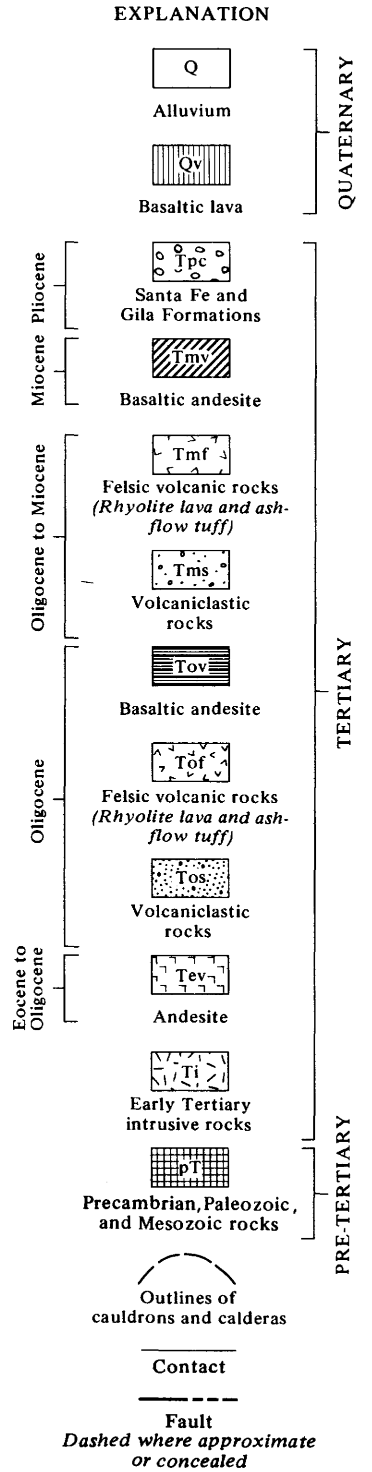

FIGURE 11.—Continued.

Formation, and it has yielded radiometric dates of 42-31 m.y., or late Eocene to early Oligocene. The South Rim Formation has been dated as 30-29 m.y.

A different but partly equivalent volcanic sequence occurs in the southern Davis Mountains to the north, where thick volcaniclastic units separated by thinner, widely traceable flows and ignimbrites project in prominent escarpments and cuestas. The volcanic components thicken and merge northward toward eruptive centers in the core of the Davis Mountains. The upper part of the sequence, approximately equivalent to the South Rim Formation, includes the Mitchell Mesa Ignimbrite, and at the top the Rawls Basalt, both of which are extensive.

The succession in the Rim Rock area farther west is notable for its abundant vertebrate remains, which have been correlated with radiometric dates from associated volcanic layers (Wilson and others, 1968). The lowest tuff unit contains a Uintan vertebrate fauna, and volcanic units directly below and above are 40 and 38 m.y. old respectively. The four higher vertebrate faunas represent different parts of the Duchesnian Stage, near the Eocene-Oligocene boundary, and associated volcanic layers have yielded radiometric ages of 38-34 m.y. Above the vertebrate-bearing beds is the base-line unit of Brite Ignimbrite with an early Oligocene age of 33-29 m.y. Mafic dikes which cut the volcanic rocks of the area have Miocene ages of 23-18 m.y. (Dasch and others, 1969).

One of the youngest units in the volcanic sequence is the Perdiz Conglomerate, which forms extensive gravel hills and plains east of the Rim Rock and south of Marfa. It is composed of clasts of a wide variety of volcanic rocks eroded from the older units, as well as clasts of Cretaceous rocks. It contains a few Tertiary fossils, but its precise age is undetermined.

UPPER TERTIARY VOLCANIC ROCKS (Tmv, Tpv)

Upper Tertiary volcanic rocks form nearly two-thirds of the surface area of the Cenozoic volcanic fields in the western United States (figs. 12, 13) and cover a span extending from about 26 m.y. to about 2 m.y. ago, or about 23 m.y. On the Geologic Map the volcanics are differentiated by age as Miocene and Pliocene volcanics (Tmv, Tpv), in places on rather tenuous evidence, but in this account it is convenient to consider them together, area by area, rather than by age.

The upper Tertiary volcanic rocks form a large and complex assemblage. On the Geologic Map, a compositional distinction is made between upper Tertiary andesites (uTa) in the Cascade Range of the Northwestern States and felsic volcanics (Tmf, Tpf), mainly rhyolites and ash-flow tuffs, in the region to the southeast. The remaining undifferentiated volcanics (Tmv, Tpv) are dominantly basaltic but include mixed associations and some small areas of felsic volcanics.

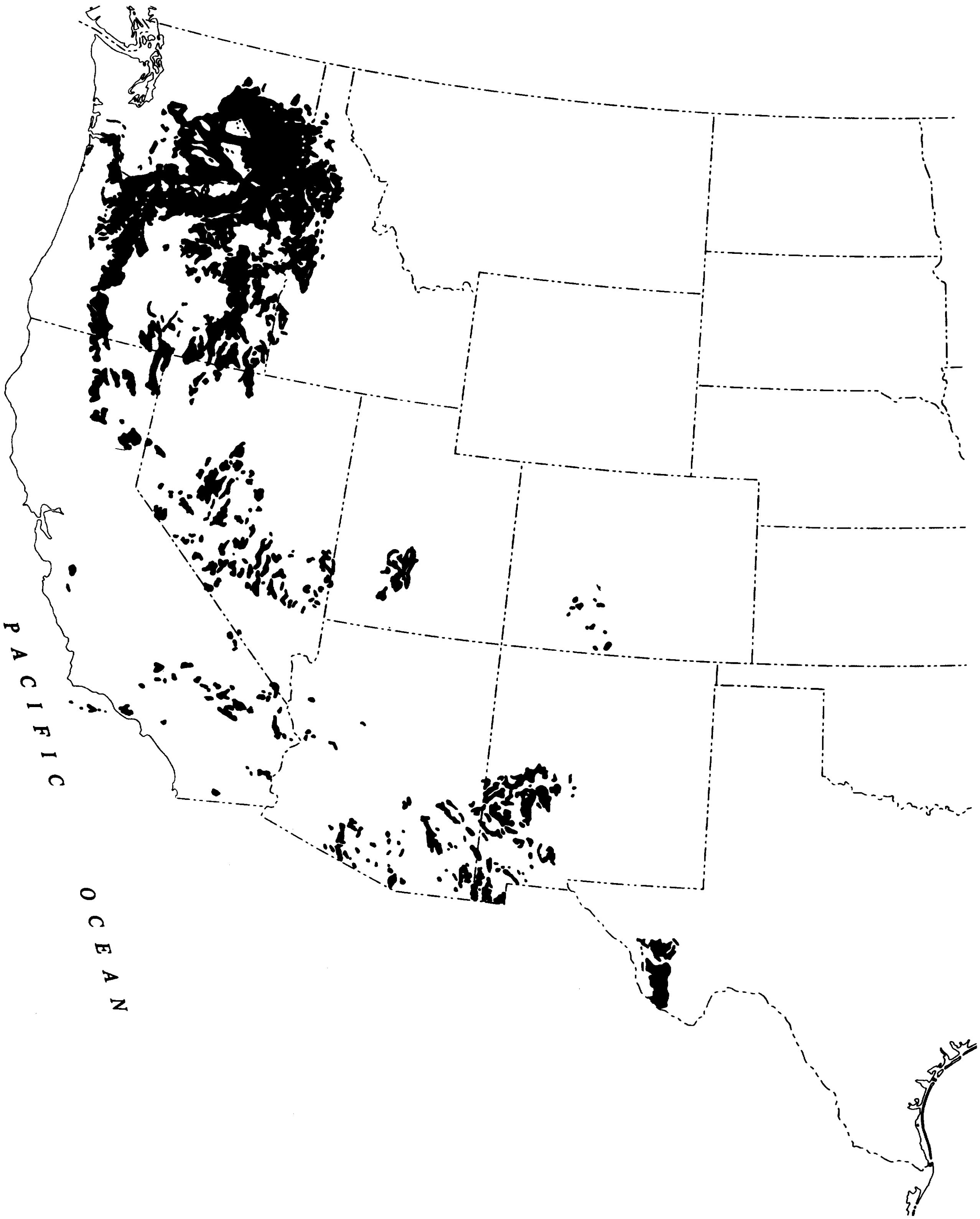

FIGURE 12.—Map of western United States showing distribution of Miocene volcanic rocks as represented on Geologic Map of the United States (units Tmv, Tmf, uTa).

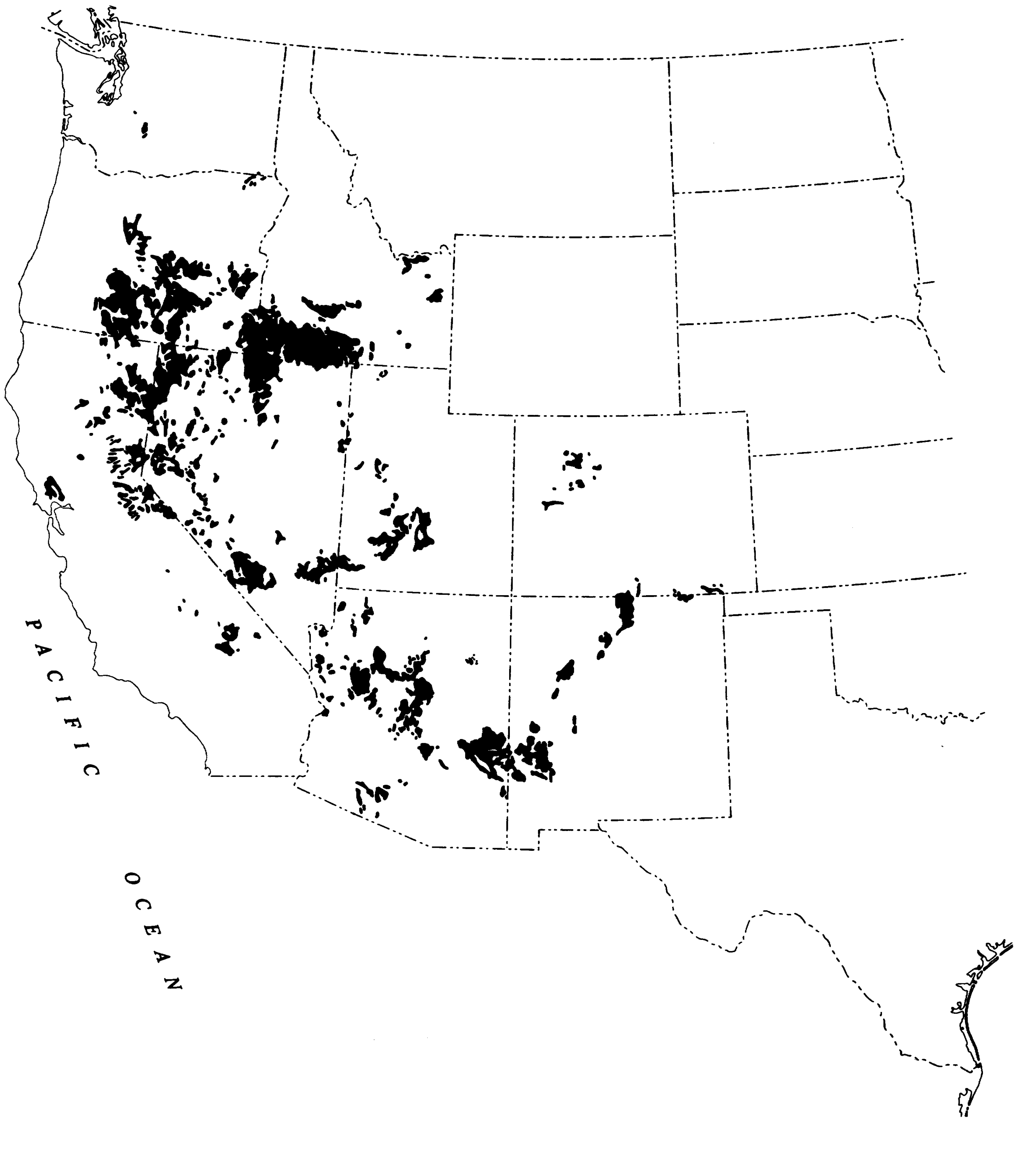

FIGURE 13.—Map of western United States showing distribution of Pliocene volcanic rocks as represented on Geologic Map of the United States (units Tpv, Tpf).

The passage from early Tertiary to late Tertiary time is characterized by a change from a dominantly calc-alkalic intermediate or andesitic regime to one of more varied volcanism (Christiansen and Lipman, 1972, p. 279-284). Basaltic fields are extensive, notably in the Columbia River Plateau to the northwest, but there are also bimodal basalt-rhyolite fields, as in the Great Basin, as well as differentiated basaltic and alkalic fields, and complex fields. The change from the earlier to the later volcanic regimes was not simultaneous across the region, but appears to have begun earlier in the south, toward the end of the Oligocene, and to have progressed northward in Miocene time and later.

Onset of the later volcanic regime was a manifestation of the dominant tensional tectonic state that began in the western part of the United States during the later Cenozoic. It was accompanied at least in its earlier phases, by extensional Basin and Range block-faulting. The earlier mixed volcanics spread indiscriminately across an unfaulted terrain, but later volcanics were closely related to the development of block-faulted basins and ranges. Ultimately, this tectonism and volcanism is related to plate motions on the Pacific Ocean floor to the west (Christiansen and Lipman, 1972, p. 279-284).

UPPER TERTIARY ANDESITES OF WASHINGTON (uTa)

The andesitic volcanism of the Cascade Range in Washington, Oregon, and California, which began during the early Tertiary, continued during the later Tertiary and the Quaternary. The later Tertiary andesitic eruptions built the High Cascades east of the lower western Cascades that had been formed by the older andesites.

In Washington, the upper Tertiary andesites form smaller, more disconnected areas than those farther south. Early in the century they were designated the Keechelus Andesite by Smith and Calkins (1906) from exposures in the Snoqualmie quadrangle on the east side of the range. These geologists recognized, however, that their unit was apparently composite, with a body of older altered andesitic volcanics, separated from younger, much fresher volcanics by an obscure unconformity. Subsequently, the name Keechelus has been extended to other parts of the Cascade Range in Washington, and misapplied to a considerable variety of andesitic units, ranging in age from Eocene to Pliocene (Waters, 1961a, p. 43-47).

Much later, volcanics equivalent to the lower Keechelus were subdivided and named in Mount Rainier National Park, southwest of the Snoqualmie quadrangle (Fiske and others, 1963, p. 20-30). The lower subdivision, the Stevens Ridge Formation, lies unconformably on the Ohanapecosh Formation, described previously (p. 51), and is about 3,000 feet (900 m) thick. In consists of flows and volcaniclastic rocks, generally light-colored and quartz-bearing. Ash-flows are abundant in the lower part and give place upward to coarse volcaniclastic rocks. The Stevens Ridge contains a middle Oligocene to lower Miocene oreodont and other fossils which indicate about the same age. The overlying Fife Peak Formation, about 2,400 feet (730 m) thick, consists of olivine basaltic and andesitic lavas, darker colored than the Stevens Ridge, with minor interbedded rhyolite flows and volcaniclastic rocks. No fossils have been found in the Fife Peak, but it lies stratigraphically between the late Oligocene to early Miocene Stevens Ridge Formation, and the late Miocene Yakima Basalt that overlaps it on the east.

The Stevens Ridge and Fife Peak are intruded by the Tatoosh granodiorite pluton which forms the foundation of the Mount Rainier volcano; this pluton is equivalent to the Snoqualmie Granodiorite that intrudes the Keechelus rocks of the Snoqualmie quadrangle. Both the Tatoosh and Snoqualmie plutons were explosively unroofed late in their history and gave rise to associated andesitic volcanics. These products have largely been eroded in the Mount Rainier area but are extensively preserved in the Snoqualmie area, where they are the upper unit of the Keechelus Andesite. Unlike the lower Keechelus, which underlies the Yakima Basalt, the upper Keechelus overlies it, and interfingers eastward with the clastics of the Ellensburg Formation of Pliocene age.

UPPER TERTIARY ANDESITES OF OREGON AND CALIFORNIA (uTa)

The upper Tertiary andesites of Oregon and California form a broader, more continuous outcrop band than in Washington, and they are mainly younger or largely of Pliocene age (Williams, 1942, p. 17-19; Macdonald, 1966, p. 71-74).

The High Cascades of Oregon form a lofty plateau surmounted by steep-sided shield volcanoes of olivine basalt and olivine-bearing andesite, largely of Pliocene age, above which rise the still higher Quaternary composite andesitic cones that form a chain along the crest. The Quaternary volcanics form only a small part of the volume of the High Cascades; the preceding Pliocene volcanics were far more voluminous. The earlier eruptions were largely quiet effusions of mafic lava of striking uniformity. Part of the lava escaped from fissures along the western border of the belt and flowed westward down canyons cut through the lower Tertiary lavas of the western Cascades. Toward the south end of the Cascade Range in California, the andesites of the High Cascades rest on the Tuscan Formation, dated by fossil plants as of Pliocene age; here, the lavas themselves are late Pliocene or even younger.

COLUMBIA RIVER GROUP OF WASHINGTON, OREGON, AND IDAHO (Tmv)

All the Columbia Plateau in southeastern Washington, northeastern Oregon, and west-central Idaho is covered by the basalts of the Columbia River Group. These form a terrane unique in the United States, although duplicated in other plateau basalt fields elsewhere in the world.

The basalts fill the recess of the Columbia arc in the Mesozoic and older metamorphic and plutonic rocks, which are exposed in the highlands to the southeast, east, and north. Westward, they have a complex relation with the upper Tertiary andesites of the Cascade Range, which are partly older, partly younger. Around the edges of the plateau, the basalts rise to altitudes of 5,000 feet (1,500 m) or more, but near the center their top is close to sea-level; the basinlike form is still more accentuated at the lower surface of the basalt flood. Over most of the plateau the basalts are flat-lying and virtually undeformed, but along their west side in Washington they are thrown into steep-sided, west-northwest-trending anticlines as a result of deformation during the Pliocene, through which the Columbia, Yakima, and other rivers have cut narrow antecedent gorges (Waters, 1955, p. 675–676).

The Columbia River basalts cover an area of 100,000 square miles (300,000 km^2) and have a volume of at least 35,000 cubic miles (125,000 km^3). Exposed sections near the edges of the plateau are as much as 5,000 feet (1,500 m) thick. In the center of the basin they must be very much thicker; here, a well drilled to more than 10,000 feet (3,000 m) failed to reach their base.

The flows were spread out on land, and columnar jointing is characteristic. At the tops of many flows are weathered zones, and occasional sedimentary intercalations that contain the remains of forests that were engulfed by the lavas. Individual flows average 75-200 feet (25-60 m) thick, but some are more than 400 feet (120 m) thick. The flows were very fluid when erupted; many of them have been followed for more than 120 miles (190 km) without reaching their edges.

The basalt flows have well-defined sequences that are recognizable over wide areas, making possible a subdivision of the Columbia River Group into formations and members, as first recognized by Waters (1961b) (fig. 14). The younger unit, and by far the most extensive, is the Yakima Basalt, originally named in the western part of the field, but which covers more than two-thirds of the northern part of the plateau as far east as Idaho. Beneath it on the south are smaller areas of older units—the Picture Gorge Basalt on the north flank of the Blue Mountains uplift, and the Imnaha Basalt in the

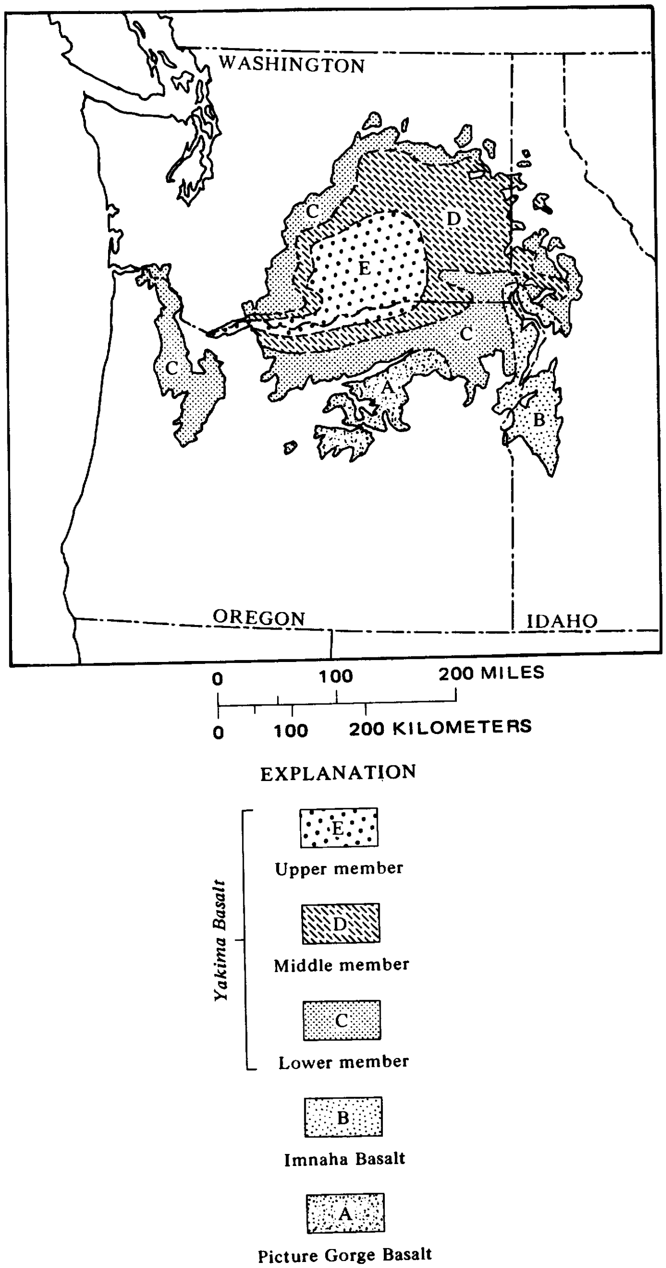

FIGURE 14.—Map of Columbia River Group of Miocene basalts in Washington, Oregon, and Idaho, showing in a very generalized manner the distribution of its subdivisions. (After Wright and others, 1973.)

Snake River area farther east. The last two units are probably nearly contemporaneous but differ somewhat in composition. They are separated from the overlying Yakima by unconformities with slight angular discordances. The Yakima Basalt, in turn, is divisible into three unnamed members (Wright and others, 1973, p. 371-374), the lower two of which correspond to the original Yakima Basalt. The upper member, preserved only in the center of the field, is more or less equivalent to the sedimentary rocks of the Ellensburg Formation on the west side.

Radiometric ages by the K/Ar method of the basalts of the Columbia River Group indicate that they were extruded during an interval of about 9 m.y. The Picture Gorge Basalt has been dated between 21 and 15 m.y., and the Yakima Basalt between 20 and 15 m.y. (Gray and Kittleman, 1967), or from early to late Miocene. The dates do not seem to confirm the considerable hiatus between the older and younger basalt formations that is suggested by the stratigraphic evidence. The highest member of the Yakima, which is equivalent to the Ellensburg Formation, probably extends into the early Pliocene.

The basalts of the Columbia River Group are monotonously uniform tholeiites, composed of pigeonite, labradorite, and magnetite-rich glass, and virtually without olivine. They differ little in composition through 3,000-foot (900-m) sections. There are, nevertheless, subtle compositional differences between the successive stratigraphic units (Waters, 1961b, p. 591-604; Wright and others, 1973, p. 377-383). The Picture Gorge and Imnaha flows contain about 5 percent olivine, 47-50 percent silica, and notably higher percentages of alumina, magnesia, and lime than the younger flows. The Yakima flows contain 53-54 percent silica, much potash and titania, and very little olivine. The flows of the highest member are again olivine-bearing.

The Columbia River flows were erupted from fissures rather than from volcanoes; they were produced in a tensional regime. Several dike swarms have been identified, mostly on the southeast and south sides of the plateau, from which the basalt flowed northward. The largest of these is the Chief Joseph (= Grand Ronde) swarm in northeastern Oregon, where there may be as many as 21,000 north-northwest-trending dikes that extend for 165 miles (265 km) or more (Taubeneck, 1970; Waters, 1961b, p. 586). Another group, the Monument Swarm, occurs farther west along the John Day River on the north side of the Blue Mountains uplift. There are smaller swarms along the edge of the field to the west and northwest. The dikes are prominently exposed on canyon walls and in roadcuts but are difficult to trace across the intervening forested uplands, where they are much weathered. They are therefore incompletely mapped and are only inadequately represented on the Geologic Map, where a few of the many dikes of the Chief Joseph and Monument swarms are shown.

As a result of the northward flow of the basalt, marginal lakes and sedimentary basins were ponded against the adjacent highlands, producing the Latah Formation on the north and Payette Formation on the east, both of Miocene age, and the somewhat younger Ellensburg Formation on the west. The basalts also flowed westward into western Oregon and Washington through a sag in the older volcanics of the Cascade Range near the site of the present Columbia River, where they assumed a pillowed subaqueous phase along the Pacific shoreline of the time and mingled with other Miocene basalts derived from local centers (Snaveley and others, 1973, p. 388-391).

SOUTHEASTERN OREGON AND NORTHEASTERN CALIFORNIA

South of the basalt field of the Columbia River Group, beyond the Blue Mountains uplift, Cenozoic volcanic rocks underlie all the surface in southeastern Oregon and in the Modoc Plateau of northeastern California as far as northern Nevada. Unlike the Columbia River basalts, these volcanics are much broken by Basin and Range block-faulting and are much more varied, both in composition and age. Miocene volcanic rocks emerge in the higher uplifts, followed by Pliocene volcanics and volcaniclastic sediments, and in the lower areas by Quaternary volcanics (Walker, 1970; Macdonald, 1966, p. 89-95).

The Miocene includes several thick bodies of basalt (Tmv), such as the Steens Basalt of Steens Mountain in southern Oregon, and the Warner Basalt of the Warner Range in northeastern California. These units are also identifiable in adjacent ranges, although it is doubtful that they formed a continuous sheet. In California, moreover, the term Warner Basalt has been used for basalts at different stratigraphic levels, some of which are Pliocene. The Steens Basalt is as much as 5,000 feet (1,500 m) thick in its type area, but the Warner Basalt is thinner. The Steens Basalt has been dated by the K/Ar method as 15-16 m.y. old, or about the same age as the main part of the Columbia River Group, but it and the other basalts of the region are dominantly alkali olivine basalts, rather than tholeiitic like the Columbia River lavas; some of the flows are nonporphyritic high-alumina basalts.

Individual flows are mostly thinner than those of the Columbia River, being mostly 20 feet (6 m) thick or less, and columnar jointing is rare. The Strawberry Volcanics on the south flank of the Blue Mountains uplift are mainly basaltic like the rest, but they pass upward into more felsic dacitic and rhyolitic lavas (Tmf).

The overlying rocks, mainly Pliocene, are a more complex assemblage, formed while block-faulting was in progress. They include sheet basalts and basalts erupted from shield volcanoes (Tpv), some dated at 9 m.y., and also large volumes of felsic volcanic rocks (Tpf), which form tuffs, flows, and domes. In places these pass into volcaniclastic sedimentary rocks (Tpc). There is, however, a notable absence of andesites and other intermediate volcanics. For the most part, the subdivisions of the Pliocene rocks have not been named, but the Danforth and Harney Formations have been distinguished in southern Oregon, where they are applied to mafic and felsic tuffs and volcaniclastic sediments that overlie the Steens Basalt. In northeastern California is the Alturas Formation, largely of lacustrine origin, composed of diatomite, tuffaceous silty and sandy shale, and sandstone, which contains Pliocene plants and mammals. Westward, the Pliocene volcanics mingle with the east edges of the upper Tertiary andesites of the Cascade Range.

SNAKE RIVER PLAIN OF SOUTHERN IDAHO

East of the region just discussed is the Snake River Plain, which extends across southern Idaho. The plain is a downwarp transverse to the earlier Cordilleran structures, extending northwestward in its western part and northeastward farther east, with a length of nearly 350 miles (550 km). It is entirely a late Cenozoic feature, probably caused by crustal rifting, and has been filled thickly by Pliocene and Quaternary volcanic rocks and associated sediments, beginning with felsic volcanics (Tpf) and changing to mafic later (Tpv, Qv) (Malde and Powers, 1962).

The initial part of the sequence is the Idavada Volcanics, which are exposed in a wide band in southwestern Idaho, sloping northward toward the axis of the plain. Small outliers project from beneath the younger lavas on the north side of the plain, and in smaller areas along the edges farther east, suggesting that the Idavada extends beneath the axis of the plain. In southwestern Idaho the Idavada is as much as 3,000 feet (900 m) thick and lies unconformably on older mineralized volcanics, largely of Miocene age. The Idavada Volcanics consist of welded ash-flow tuffs and rarer lavas that are partly silicic latite and partly rhyolite. A prominent component is the Cougar Point Tuff that forms the rim of the south-facing cuestas along the Nevada border, overlooking the older volcanics (Coats, 1964, p. 13-15). The sedimentary parts of the formation in the western part of the plain contain fossil plants, land snails, and diatoms of lower Pliocene age, but fossils of apparently somewhat younger age occur farther east.

Overlying the Idavada Volcanics in the uplands south of the western part of the plain is the Banbury Basalt of the Idaho Group (the various subdivisions of the group have already been described in the section on "Idaho Group"). The Banbury is as much as 900 feet (290 m) thick, but it thins southward to a feather edge along the Nevada border. Mammals and other fossils in sedimentary intercalations are of middle Pliocene age, and the basalt has yielded a radiometric age of 9 m.y. Overlying volcanic rocks of the Snake River Plain are of Quaternary age.

GREAT BASIN OF NEVADA AND ADJACENT STATES

Miocene and Pliocene volcanic rocks (Tmv, Tpv) form an extensive and complex assemblage in the Great Basin of Nevada, and extend into Utah and California. Important parts of the assemblage are felsic (Tmf, Tpf); they are shown separately on the Geologic Map. Felsic eruptions began in eastern Nevada and southwestern Utah in the late Oligocene, as described in the section on "Eastern Great Basin," and progressed westward and southwestward during Miocene and Pliocene time (Armstrong and other, 1969; McKee and Silberman, 1970; McKee and others, 1971; Silberman and McKee, 1972).

The Tertiary volcanic sequence in central and western Nevada falls into three groups: andesitic and dacitic flows with ages of 36 to 34 m.y. (included on the Geologic Map in the lower Tertiary volcanics (lTv); rhyolite ash-flows with ages from 34 to 20 m.y. (divided on the map between lower Tertiary and Miocene volcanics, lTv, Tmf); and alkali basaltic and andesitic flows with ages less than 17 m.y. (mainly shown as Tpv). The first two groups were spread widely over a featureless terrain; the third group accompanied and followed the beginning of block-faulting and the development of Basin and Range structure.

The sequence of volcanic rocks in Lander and Churchill Counties is typical of central Nevada (McKee and Silberman, 1970; McKee and Stewart, 1971). The lower Tertiary andesite and dacite flows (lTv) are followed by Miocene ash-flow tuffs (Tmf) more than 1,500 feet (450 m) thick, which consist of a succession of ash-flows or cooling units. These are widely traceable from range to range but were derived from different centers and wedge out laterally in various directions, so that not all the units occur in single sections. The oldest formation is the Edwards Creek Tuff, composed of five cooling units, with an age of 27 m.y. The Bates Mountain Tuff, commonly composed of three cooling units, has an age of 24 m.y.; and the New Pass Tuff, a single cooling unit, has an age of 22 m.y. In northern Lander County the oldest tuff formation is the Caetano Tuff, which is preserved in an east-west belt that extends across three or four of the ranges. In northern Lander County, the ash-flow tuff sequence is followed unconformably by the upper volcanic sequence (Tpv); here, basalt and basaltic andesite flows as much as 1,000 feet (300 m) thick, with ages of 15–10 m.y., stand in mesas and cuestas that overlook the older volcanics. These basalts and andesites are closely related to the volcanics adjoining the Snake River Plain to the north, already described.

In western Nevada the Miocene ash-flow deposits are scantily developed, and most of the volcanic rocks belong to the younger sequence (Tpv). They were erupted from local centers, where they may attain thicknesses of several thousand feet, but their total volume is less than that of the earlier volcanics. Their composition is varied, with dominant calc-alkaline andesite and dacite, but including some flows of rhyolite and alkali-olivine basalt. They include the volcanic sequence in the Virginia and Carson Ranges (Thompson and White, 1964, p. 12–18), and farther south those in the Bodie Hills, the Goldfield Hills, and the Silver Peak Range (Robinson and others, 1968). The best known sequence, in the Virginia and Carson Ranges, has at the base the Alta Formation, of soda trachyte and hornblende andesite, with some fossil plants of Oligocene or Miocene age, followed by the thicker and more varied mass of the Kate Peak Formation, composed largely of hornblende andesite flows and flow-breccias, with some flows of basalt and rhyolite, and much tuff-breccia. Hydrothermally altered parts of the Alta and Kate Peak Formations were the hosts of the fabulous Comstock Lode of the Virginia City district. The Kate Peak is apparently intergradational with the Alta Formation, and its upper part interfingers with the sedimentary Truckee Formation of the adjoining basins. Fossil plants indicate that the Kate Peak is largely of Pliocene age (Tpv). The Kate Peak and Truckee are overlain unconformably by the basalts of the Lousetown Formation that is largely Pleistocene (Qv).

A different sequence of upper Tertiary volcanic rocks occurs in southern Nevada, where they form an extensive and nearly unbroken field centering in the Nevada Test Site of southern Nye County and attain a thickness of as much as 40,000 feet (12,000 m) (Ekren, 1968). Miocene ash-flow tuffs crop out around the edges, but the most extensive surface rocks are Pliocene ash-flow tuffs (Tpf) that were erupted from local calderas, two of which, the Timber Mountain and Black Mountain calderas, are still expressed at the surface and are shown on the Geologic Map. Older calderas have been covered by the younger volcanics and are known only from drilling and geophysical surveys. Radiometric ages by the K/Ar method range from 27 m.y. (early Miocene) for the oldest ash-flow tuffs to 6 m.y. (Pliocene) for the youngest (Marvin and others, 1970). Minor basalt flows (Tpv) overlie the youngest ash-flows and are related to the development of the Basin and Range structure.

SIERRA NEVADA AND COAST RANGES OF CALIFORNIA

On the long western slope of the Sierra Nevada, between its crest and the Great Valley, are many erosional remnants of Tertiary volcanic rocks—abundant in the north, sparse in the south—which are parts of the "Superjacent Series" of the early reports which lies unconformably on the "Bedrock Series" of the Mesozoic and earlier rocks. The Superjacent Series includes accumulations that formed during a prolonged period, from Eocene to Pliocene, and in the northern Sierra, at least, was originally a much more extensive cover. The superjacent rocks were laid down on a surface that sloped westward like the present range, but much more gently, as much of the great tilting and uplift of the Sierra occurred during the late Pliocene and early Pleistocene, before which the surface was more or less confluent with that of the Great Basin to the east. Most of the earlier Tertiary deposits, although significant, are of small extent so that on the Geologic Map the superjacent rocks are largely indicated as Pliocene volcanics (Tpv), themselves generalized and reduced in area at the expense of the bedrock formations.

The oldest Tertiary deposits, of Eocene age, occur only in the northern Sierra Nevada. The Ione Formation (Tec) of the Sierra foothills, a continental and littoral deposit, extends upslope into the Auriferous Gravels, which were laid down in the channels of vanished rivers. They are followed by various basaltic and andesitic units of Eocene and Oligocene age (Durrell, 1966, p. 187–189), a few of which are shown on the Geologic Map as lTv.

Much more extensive, both in the northern and central Sierra Nevada, are the Miocene and Pliocene volcanic formations (Durrell, 1966, p. 189-192; Slemmons, 1966). In the central Sierra they include the rhyolitic Valley Springs Formation, the andesitic Relief Peak Formation, the latitic Stanislaus Formation, and the andesitic Disaster Peak Formation, the first two Miocene, the last two Pliocene, as indicated by radiometric dating and fossil plants. An interesting feature of the younger lavas are the "Table Mountains" which follow the sinuous courses of ancient river beds but now rise above the surrounding terrain. In the foothills the equivalent of the younger volcanics is the Mehrten Formation, composed largely of andesitic debris.

In the southern Sierra Nevada, Tertiary volcanic rocks form only widely spaced outliers (Bateman and Wahrhaftig, 1966, p. 139-145), a few of which are shown on the Geologic Map (Tpv). Probably they were never much more extensive, as this part of the Sierra had much more erosional relief during the Tertiary than farther north, perhaps 4,000-6,000 feet (1,200-1,800 m); the flows accumulated in valleys below the higher summits. The flows are mainly basaltic and andesitic, and different outliers have been dated radiometrically as between 9 m.y. and 2 m.y.

In the Coast Ranges west of the Sierra Nevada upper Tertiary volcanic rocks were erupted from a number of widely spaced centers and interfinger laterally with the contemporaneous Tertiary sediments, some of which themselves contain much volcanic debris.

In the southern Coast Ranges and farther south, the volcanics are mainly of lower Miocene (pre-Monterey) age. In the western Santa Monica Mountains of the Transverse Ranges is a Miocene volcanic pile 5,000 feet (1,500 m) thick of submarine andesites and basalts, with extensive associated shallow intrusives. The volcanic field extends westward into the Channel Islands and is well represented on Santa Cruz Island. Much farther south, San Clemente Island is largely formed of subhorizontal Miocene lava flows. Farther north, in the southern Coast Ranges west of the San Andreas fault, are the Miocene volcanics of the Pinnacles area in the Gabilan Range, composed of rhyolite flows, tuff, and breccia; and the lower Miocene Mindego Formation of the Santa Cruz Mountains of basalt, pillow lava, and tuff, with an age of about 23 m.y. East of the San Andreas fault in the southern Diablo Range (not far from the Pinnacles area) are the middle Miocene andesite and basalt flows and agglomerates of the Quien Sabe area.

Farther north in the Coast Ranges, east of the San Andreas fault, the volcanics are younger. In the Berkeley Hills east of San Francisco Bay, the Berkeley Group at the top of the thick nonmarine Pliocene sequence consists of several persistent lava units, separated by clastic units; it has been dated by the K/Ar method as between 12 m.y. and 5 m.y. old. Closely related to the Berkeley Group, although somewhat younger, are the more extensive Sonoma Volcanics north of the bay, of andesite, basalt, and rhyolite flows, tuffs, breccias, and agglomerates, with minor pumice and obsidian, and water-laid volcaniclastic sediments. The Sonoma Volcanics have yielded an age of about 3 m.y.

SOUTHERN ROCKY MOUNTAINS

Upper Tertiary volcanics are less extensive in the Southern Rocky Mountains than the more voluminous lower Tertiary volcanics already described, but they occur in widely separated areas.

West of the Rocky Mountains in northwestern Colorado are many erosional outliers of basaltic volcanics. They were labeled QTv on the Geologic Map of Colorado (1935), but obviously could not be Quaternary, as they form mesas on the "top of the country," such as Grand Mesa east of Grand Junction and the Flat Tops in the northern part of the White River Plateau. On the Geologic Map they are classed as Pliocene (Tpv), but later geologic work indicates that the outliers have a greater range of later Tertiary ages (Larson and others, 1975).

The rocks shown as Tpv on the map are mainly of two age groups. The older volcanics are of Miocene age, with radiometric ages between 24 and 20 m.y., and interfinger laterally with the Browns Park Formation. A younger group is of late Miocene and early Pliocene age, with radiometric ages between 15 and 9 m.y. Both groups are represented in the Flat Tops outlier in the northern White River Plateau, but only the second occurs in Grand Mesa farther west. A third group about 8 m.y. old was erupted after considerable uplift and faulting had occurred in the region. Minor Pleistocene basalts (not shown on the map) occur in some of the canyons of the area.

The Miocene volcanics at the top of the sequence in the San Juan Mountains have already been noted (p. 57). These, and the earlier Oligocene volcanics, preceded the downwarping and downfaulting of the Rio Grande depression east of the mountains, and its local representative, the San Luis Valley. Formation of the depression was accompanied by a new cycle of basaltic volcanism, beginning in Pliocene time in the north, and continuing into Quaternary time farther south (Lipman and Mehnert, 1975). The most extensive flows, the Servilleta Formation (Tpv) are flat-lying olivine tholeiites which spread over the Santa Fe Formation in the depression to a thickness of 650 feet (200 m) to form a broad plateau west of Taos, New Mexico, and have been dated as between 4.5 and 3.6 m.y.

In the Great Plains east of the Sangre de Cristo Mountains in northeastern New Mexico and southeastern Colorado a unique volcanic field developed in late Cenozoic time in a region that had had little prior igneous history (Stormer, 1972). Along the New Mexico-Colorado boundary, the lofty Raton Mesa and Mesa de Maya are capped by olivine basalt flows with a Pliocene age of about 8 m.y. (Tpv); the eastern tip of the volcanic outliers extends into the west corner of Oklahoma. During the Quaternary basalt flows covered the area to the south, each flow lying on successively lower erosion surfaces. Eruptions in this field were probably genetically related to those that accompanied the formation of the Rio Grande depression to the west.

VOLCANIC FIELDS OF COLORADO PLATEAU

The west and south edges of the Colorado Plateau, southwest of the Rocky Mountains, in Utah, Arizona, and New Mexico, are marked by a chain of volcanic fields erupted from different centers.

For the northernmost field, that in the High Plateaus of southern Utah, little information was available at the time of compilation of the Geologic Map, except for Major Dutton's report for the Territorial Surveys (1880), and local reports on the Marysville mining district. Only recently have more comprehensive data become available (Anderson and Rowley, 1975), which indicate that some revision of representation on the Geologic Map will be required.

On the Geologic Map the volcanics of the High Plateaus are shown as of Miocene and Pliocene age (Tmv, Tpv). More recent data indicate that although the base is Oligocene with a radiometric date of 30-25 m.y., the bulk is of Miocene age with radiometric dates between 25 and 19 m.y. (Bassett and others, 1963; Anderson and Rowley, 1975). The overlying sedimentary Sevier River Formation (Tpc) and associated basalt flows are Pliocene.

The broad Oligocene ash-flow tuffs of the Great Basin, such as the Needles Range and Isom Formations, extend into the western part of the High Plateaus, where they are succeeded by varied local volcanic accumulations. In the Marysville area, where the latter exceed 5,000 feet (1,500 m) in thickness, the lower part (Bullion Canyon Formation in the north, Mount Dutton Formation farther south) consists of rhyodacite and basalt flows and associated shallow intrusives, which pass outward into volcanic breccias, ash-flow tuffs, and interbedded sediments. In the upper part of the pile are several more persistent named units of basalt, rhyolite, and tuff, the youngest of which has been dated at 19 m.y. (late Miocene). The outer edges of the accumulation cap the Fish Lake and Aquarius Plateaus on the east, and the Markagunt Plateau and other mountains on the southwest and west. Although the edges of the volcanic field have been worn back by erosion, its present extent probably approximates the original outlines.

In Pliocene time, the Miocene volcanic rocks were broken into separate blocks by the great faults along the west side of the Colorado Plateau (the Paunsagunt, Sevier, and others), and the continental beds of the Sevier River Formation were deposited on the downfaulted blocks.

On the Geologic Map of Arizona (1969), the upper Cenozoic volcanics along the edge of the Colorado Plateau are represented as Qv, TQv, and Tv. In compiling the Geologic Map, it was assumed that the first group was Quaternary (Qv), the second Pliocene (Tpv), and the third Miocene (Tmv). In general, this classification has been confirmed by later more detailed data.

The plateaus in the western part of the Grand Canyon district of northwestern Arizona exhibit a sequence of basalts of Pliocene and Quaternary ages (shown as Tpv on the map), whose eruptions were closely related to the block-faulting and canyon cutting (Hamblin, 1970). They are divisible into four groups, of which only the first is Pliocene, with ages of 6 or 7 m.y. This lava flowed onto a plain unrelated to the modern topography and is interbedded with stream gravels derived from the south; all the block-faulting and canyon-cutting was later. The three later groups are more closely related to modern drainage, and formed during progressive erosional lowering. The youngest basalt, of late Quaternary age, poured into the present canyon at Vulcan's Throne, temporarily damming the Colorado River.

Farther southeast in Arizona is an extensive complex of volcanic fields extending southward from San Fancisco Peaks near Flagstaff to the Prescott-Jerome area (McKee and Anderson, 1971). The San Francisco Peaks are a much dissected volcanic center, whose summit rises to an altitude of 13,370 feet (4,090 m), or about 6,000 feet (1,800 m) above the surrounding plateau. Its eruptions began during the middle Pliocene, about 7 m.y. ago, beginning with basalt, followed by intermediate lavas, and ending with Quaternary basalt. In the Prescott-Jerome area to the south, an older series, the Sullivan Buttes Latite, with radiometric dates of 26–23 m.y. (late Oligocene and early Miocene) is followed by the more extensive Hickey and Milk Creek Formations, consisting of basalt flows and interbedded continental deposits, with ages of 14–10 m.y. (late Miocene and early Pliocene), confirmed by mammalian bones of Barstovian and Clarendonian ages. The edges of the somewhat younger basalts of the San Francisco field overlap the formations of the Prescott-Jerome field on the north. Block-faulting succeeded the volcanic epoch, and the continental Verde Formation was laid down in the ensuing depressions. It contains late Hemphillian mammals and its interbedded basalts have an age of about 5 m.y.

The Mogollon field at the southeast corner of the Colorado Plateau in New Mexico has already been discussed (see section on "Mogollon Plateau, southwestern New Mexico"). It is largely of Oligocene age, but the upper part of the sequence is Miocene.

UPPER TERTIARY VOLCANIC ROCKS OF SOUTHERN BASIN AND RANGE PROVINCE IN ARIZONA AND CALIFORNIA

The desert ranges of southern Arizona and southeastern California present an array of Cenozoic volcanic rocks lying on an eroded surface of the plutonic and metamorphic basement. Some of the volcanic areas have been studied in detail, but most of them are known only in a general way, and no comprehensive summary is available. Many of the volcanic rocks in Arizona have been dated radiometrically by Paul Damon and his associates at the University of Arizona (Damon and Bikerman, 1964), and Armstrong and Higgins (1973) have reported on radiometric ages in the Mojave Desert of California.

On the Geologic Map of Arizona (1969), the volcanic rocks of the southern part of the State were placed in five categories. They are listed below, along with designations adopted for them on the Geologic Map of the United States:

Geologic Map of Arizona (1969)	*Geologic Map of United States*
Quaternary volcanics (Qb, Qr)	Quaternary volcanics (Qv)
Quaternary and Tertiary volcanics (QTv, QTb, QTa)	Pliocene volcanics (Tpv, Tpf)
Tertiary volcanics (Tv, Tvs, Tvi, Tvm)	Miocene volcanics (Tmv, Tmf)
Tertiary and Cretaceous volcanics (TKv, TKa, TKr)	Lower Tertiary volcanics (lTv)
Cretaceous volcanics (Kv, Kr, Ka)	Do.

In general, the age assignments made on the Geologic Map of the United States have been confirmed by more detailed surveys and by radiometric dating. The age relations of the lower Tertiary volcanics have already been discussed (see section on "Southwestern Arizona"); most are probably Oligocene, but volcanics of Cretaceous and Miocene ages have been included in places. The Miocene (Tmv, Tmf) and Pliocene (Tpv, Tpf) volcanics have yielded ages of 25 m.y. and younger at many localities. In the Mojave Desert region to the west, all the volcanics yield ages of 22 m.y. and younger, and lower Tertiary volcanics are absent.

The different categories of volcanic rocks show progressively less deformation with age, and some of the groups are separated by unconformities. The lower Tertiary volcanics are much deformed and mineralized, whereas the upper Tertiary volcanics are merely tilted and almost unaltered; the Quaternary volcanics are flat-lying. The Basin and Range block-faulting generally began immediately after the Miocene. For example, the Galiuro Mountains east of Tucson are composed of a thick sequence of eastward-tilted Miocene volcanics, which with their basement are upfaulted against the Pliocene deposits in the San Pedro Valley to the west.

QUATERNARY VOLCANIC ROCKS (Qv, Qf)

Quaternary volcanic rocks occupy notably smaller areas than the lower and upper Tertiary volcanic rocks, but their distribution is significant in that it reflects the areas of latest crustal activity in the Cordillera (fig. 15). One belt extends southward along the Cascade Range of the Northwestern States in a series of volcanic cones that form its crest. To the east is a transverse belt centering in the downwarp or rift of the Snake River Plain and extending eastward into Yellowstone National Park and westward into central Oregon. Another more disconnected belt of Quaternary volcanics extends from northeastern New Mexico, across the Rio Grande depression, and into the southern Colorado Plateau of northern Arizona. Smaller areas occur elsewhere, notably along the edge of the Sierra Nevada in eastern California.

On the Geologic Map all the Quaternary volcanics are grouped together. It would have been instructive to separate the lower Pleistocene, upper Pleistocene, and Holocene volcanics, but we believe that this is

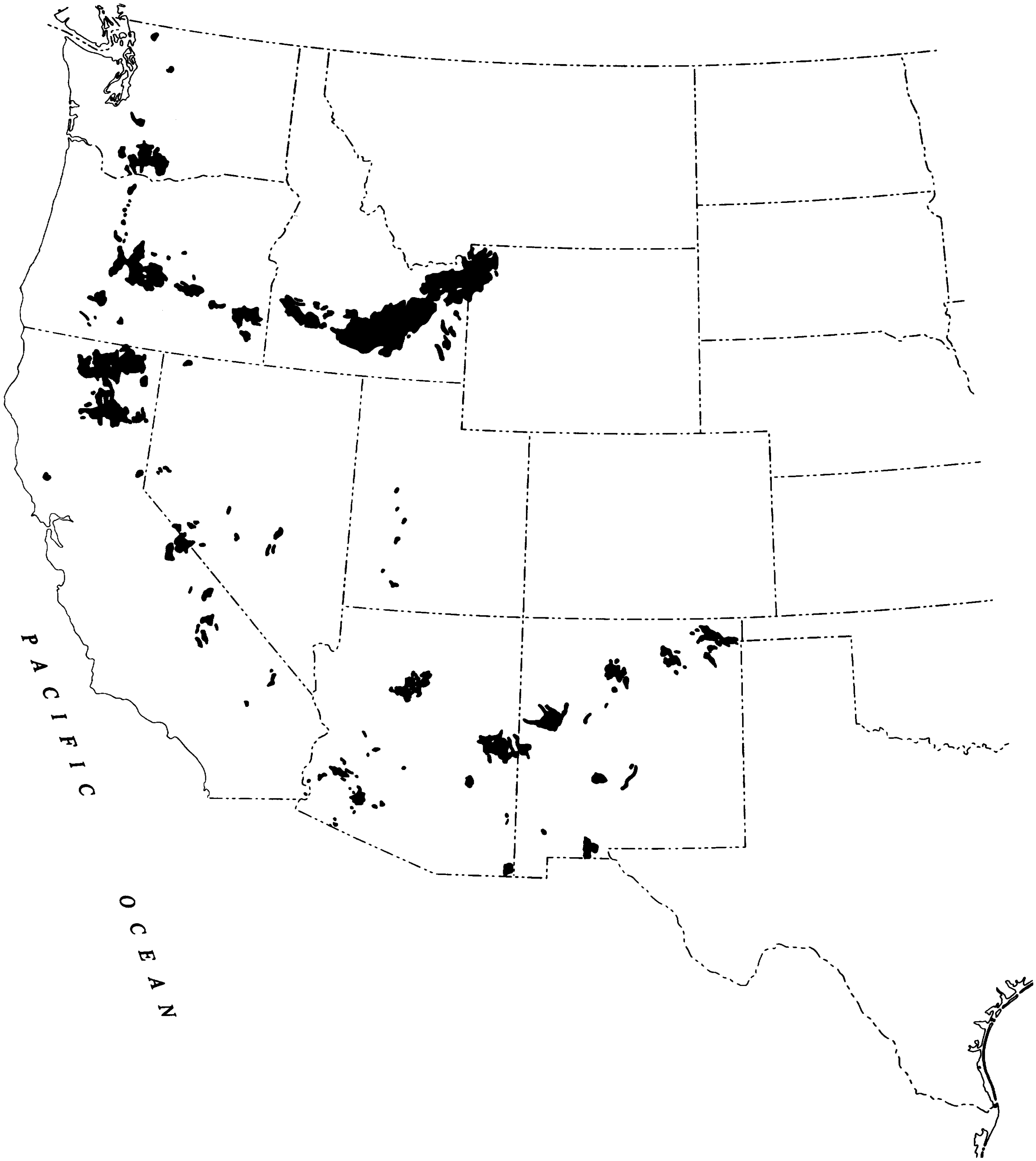

FIGURE 15.—Map of western United States showing distribution of Quaternary volcanic rocks as represented on Geologic Map of the United States (units Qv, Qf).

more appropriate on larger-scaled maps of special areas. Most of the Quaternary volcanics are basaltic, but those of the Cascade Range are andesitic, and there are significant areas of felsic volcanics (differentiated as Qf), notably in Yellowstone Park, along the edge of the Sierra Nevada and around the Valles Caldera in the Jemez Mountains of northern New Mexico.

ANDESITIC VOLCANICS OF CASCADE RANGE IN WASHINGTON, OREGON, AND CALIFORNIA

The Pliocene and older andesites of the High Cascades in the Northwestern States (uTa) are crowned by a chain of lofty volcanic cones that were built by eruptions during Quaternary time (Qv)—Glacier Peak, Mount Baker, Mount Rainier, Mount St. Helens, and Mount Adams in Washington; Mount Hood, Mount Jefferson, Mount Washington, "Mount Mazama" (Crater Lake), and Mount McLoughlin in Oregon; Mount Shasta and Lassen Peak in California. Forty miles (64 km) east of the main chain in central Oregon is the shield volcano of Newberry Caldera. The volcanoes project to imposing heights; Mount Rainier rises to 14,408 feet (4,392 m), and Mount Shasta to 14,162 feet (4,317 m); some of the others are nearly as lofty.

The geology of the High Cascades volcanoes is dealt with in many reports. Fiske, Hopson, and Waters (1963) have described Mount Rainier. Most of the fundamental work on the southern volcanoes is by Howel Williams (1932a, b, 1942, and many other papers). Higgins and Waters (1967) have reported on Newberry Caldera.

Growth of the Cascade volcanoes began well back in the Pleistocene, and some of them have a complex glacial as well as a volcanic history. Important eruptions continued well into the Holocene. Mount Mazama "blew its top" in a great eruption 6,600 years ago, creating a gaping hole that was filled by the waters of Crater Lake, and deposited a layer of ash widely toward the northeast. Mount St. Helens was built only a few thousand years ago, and Lassen Peak erupted vigorously in 1914 and 1915—the only active volcano in the Forty-eight States. Many of the other volcanoes are merely dormant, as shown by modern fumarolic activity.

The volcanoes are surrounded by small to large areas of Quaternary volcanics (Qv). In many of the northern ones the lavas extend little farther than the bases of the cones, but in California the Quaternary lavas spread well east of the Cascades in the Medicine Lake Highlands and Modoc Plateau (Macdonald, 1966, p. 83-94). Newberry Caldera is at the summit of a broad shield volcano, much more extensive than the steep-sided cones of the main Cascades.

Most of the Quaternary lavas of the Cascade Range are pyroxene andesites, but in some of the cones there is also subordinate basalt and dacite. The Quaternary volcanics east of the main range are less andesitic and more varied. The Newberry center includes basalt and rhyolite, and several prominant late flows of obsidian. Similar rocks are also prevalent in the Medicine Lake Highlands and Modoc Plateau in California.

BASALTS OF SNAKE RIVER PLAIN (Qv)

In the downwarp or rift of the Snake River Plain is the Idaho Group, Pliocene and early Pleistocene, consisting of sediments and interbedded basalt flows, which is succeeded by the Pleistocene and Holocene Snake River Group of basalt with minor sedimentary layers (Malde and Powers, 1962, p. 1212-1217). The Snake River Group forms most of the surface in the eastern half of the plain and less extensive areas farther west. The individual units are discontinuous, partly because the flows were derived from different centers and partly because they spread on an irregular topography formed during the progressive downcutting of the Snake River and its tributaries. Drill holes indicate that the rocks of the group attain a thickness of 900 feet (275 m) or more near the central axis of the plain.

The Snake River Group is divided into the Madison Basalt, Sugarbowl Gravel, Thousand Springs Basalt, Crowsnest Gravel, Sand Springs Basalt, Bancroft Springs Basalt, Melon Gravel, and Holocene lava flows. The gravels were derived from streams flowing onto the plain from surrounding highlands, probably during times of excessive runoff during the glacial periods; the Melon Gravel at the top was derived from catastrophic floods resulting from rapid draining of Lake Bonneville to the southeast. The basalts are all olivine-bearing, and different units each comprise several flows, most of which have conspicuous columnar jointing. In the areas between the present streams, the older basalts underlie level surfaces, which are covered by windblown silt and are heavily farmed. The Holocene flows are fresh and unaltered and lack soil cover. At the Craters of the Moon, about midlength in the Snake River Plain, a cluster of very recent craters follows a north-south fracture in the older lavas.

FELSIC VOLCANIC ROCKS OF YELLOWSTONE NATIONAL PARK (Qf)

East of the terminus of the Snake River Plain is a very different body of Quaternary volcanic rocks, largely of felsic composition (Qf) in the high plateau of the Yellowstone National Park area (Christiansen and Blank, 1972). It covers an area of 2,500 square miles (6,500 km^2) and radiometric dating indicates that all the rocks are less than 2 m.y. old, the youngest being about 70,000 years.

The first eruptions were great sheets of ash-flow tuff that spread widely over the terrain and culminated explosively about 600,000 years ago with the collapse of an enormous central caldera 25 by 45 miles (40 by 70 km) across in the area northwest of the present Yellowstone Lake. Because of later eruptive cover, the caldera is little expressed in modern topography; its original configuration is marked by a dashed and dotted line on the Geologic Map. The ash-flow tuffs erupted from it are exposed mostly in the uplands surrounding the caldera itself. By contrast, the smaller, nearly contemporaneous Island Park caldera west of Yellowstone Park is a prominent topographic feature.

After the early ash-flow eruptions and the collapse of the caldera, its site was buried by a younger series of rhyolitic lava flows whose upper surface forms the present Yellowstone Plateau. Late in the eruptive cycle, minor sheets of basalt spread out in areas beyond the caldera.

Following the end of eruption, the volcanic plateau was heavily covered by ice during the Wisconsin Glacial Stage (minor earlier glacial deposits are interbedded in places with the volcanics). The region remains a thermally active area, as attested by its numerous hot springs and geysers.

EASTERN BORDER OF SIERRA NEVADA, CALIFORNIA

A smaller, but significant area of Quaternary felsic volcanism lies along the eastern base of the Sierra Nevada between Mono Lake and the head of Owens Valley to the south, where eruptions occurred from about 3 m.y. ago to less than 13,000 years ago (Gilbert and others, 1968, p. 288–299). The volcanism was genetically related to the growth of tectonic-volcanic depressions in the Mono Lake basin and Long Valley farther south.

The felsic eruptions and development of present structures began about 3 m.y. ago. About 700,000 years ago the Bishop Tuff spread out as an ash-flow sheet from a center near Long Valley, flowing both southward into the head of Owens Valley near Bishop and northward into the Mono Lake basin. It overlies the Sherwin Till of Illinoisan or Kansan age. After eruption the tuff was faulted and warped, producing a fairly steep slope from Long Valley toward Owens Valley.

Events following the eruption of the Bishop Tuff include the growth of Mono Craters and other rhyolite and dacite domes on the west and south sides of Mono Lake during late Pleistocene and Holocene time. They were extruded as stiff magma which formed steep-sided domes and craters.

The Mono Lake basin and Long Valley are structural depressions, as indicated by their strong negative gravity anomalies. The depth of their volcanic and sedimentary fill has been variously interpreted as more than 10,000 feet (3,000 m) and only a few thousand feet, depending on what assumptions are made as to the densities of the filling material.

CLEAR LAKE AREA, CALIFORNIA COAST RANGES

The Clear Lake area of the northern Coast Ranges, about 60 miles (95 km) north of San Francisco Bay, records an epoch of Quaternary volcanism unique in this part of California (Anderson, 1936). The lake itself was created by volcanic damming in late Pleistocene or Holocene time. The volcanics were erupted onto the eroded surface of older rocks—to the east the thick tilted continental deposits of the Cache Formation of late Pliocene and early Pleistocene age (Tpc), and farther west the Franciscan and other Mesozoic rocks.

The area is dominated by Mount Konocti, a volcanic cone that rises 2,500 feet (760 m) above the lake on its south side, which is formed of rhyodacite lava and associated tuff and breccia. At the east end of the lake are younger flows and cinder cones of andesite, dacite, and obsidian. Solfataric activity and mineralization of sulfur and cinnabar in the lavas and bedrock still continues. Probably related to the Clear Lake volcanism is the Geysers geothermal area southwest of the lake, although it is not accompanied by eruptive activity.

JEMEZ MOUNTAINS, NEW MEXICO

Another area of dominantly felsic Quaternary volcanism occurs far to the east, in the Jemez Mountains of northern New Mexico (Smith and Bailey, 1968). The Jemez Mountains are a late Tertiary and Quaternary volcanic edifice, built mostly over the Tertiary deposits of the western part of the Rio Grande depression, but overlapping westward onto Mesozoic, Paleozoic, and Precambrian rocks of the Nacimiento uplift. The volcanics have an area of 1,500 square miles (3,900 km^2) and a maximum thickness of 5,000 feet (1,500 m).

Initial eruptions during the Pliocene were dominantly basaltic, but during later Pliocene time eruptions progressed from basalt to andesite to rhyodacite, quartz latite, and rhyolite. During the early Pleistocene they culminated in the great ash-flow sheets of the Bandelier Tuff, which were erupted from central calderas and spread widely over the surrounding terrain, where they are preserved as flat-topped mesas (Qf). Two main phases of ash-flow eruptions are dated at 1.4 and 1.0 m.y., respectively. The second phase was accompanied by the subsidence of the great Valles Caldera, 12-14 miles (19-22 km) across, still a prominent topographic feature. Small rhyolite domes were built inside the caldera, the youngest about 400,000 years ago. The region remains a high thermal area, with many solfataras and hot springs inside the caldera.

BASALTIC FIELDS OF NEW MEXICO AND ARIZONA

Aside from the felsic volcanics just described, all the Quaternary volcanism in New Mexico and Arizona was mafic. Basalts were erupted from various centers, especially across the northern parts of the two States, where they form a chain of disconnected fields extending from east of the Rocky Mountains in northeastern New Mexico, westward across the Rio Grande depression, into the southern Colorado Plateau of Arizona. The basalts flowed over the eroded surface of older rocks, and still remain as broad, nearly level plains, punctuated here and there by small craters and cinder cones. In northeastern New Mexico one of the volcanoes, Capulin Mountain, rises 2,000 feet (600 m) above its surroundings. In some areas the lavas spread on successively lower erosion surfaces, indicating that several epochs of basaltic eruption occurred. Some of the fields lie upon, or are adjacent to, areas of late Tertiary volcanism; the westermost field of northern Arizona flanks the Pliocene volcanic center of San Francisco Peaks. Other fields have little relation to prior volcanic activity.

In New Mexico, minor basaltic fields like those to the north occur at intervals down the Rio Grande depression to the Mexican border. Others are scattered over the Basin and Range province westward into southwestern Arizona, where one of the largest is in the Gila Bend area.

TERTIARY INTRUSIVE ROCKS (Ti)

Intrusive igneous rocks of Tertiary age are widely distributed in the Cordilleran region of western United States (fig. 16), but their areal extent is far less than that of the Mesozoic plutonic rocks of the same region. Although diverse in both character and age, they are shown as a single unit (Ti) on the Geologic Map. They include a few coarse-grained granitic bodies of batholithic dimensions, notably in the northern Cascade Range of Washington, in the region of the Idaho batholith of central Idaho, and in the Southern Rocky Mountains of Colorado, but most are smaller hypabyssal intrusions of shallow origin—mainly stocks and laccoliths. Most of the intrusive rocks are of early to middle Tertiary age, the earlier ones a continuation of the plutonic activity of Cretaceous time, the later intrusions representing one of more cycles of subsequent igneous activity. Some of the Tertiary intrusive rocks have already been mentioned in the discussions of the closely related volcanic rocks.

CASCADE RANGE

Some of the larger Tertiary intrusive bodies are in the northern Cascade Range of Washington, where they are embedded in the earlier metamorphic and plutonic complex but also invade the overlying lower and middle Tertiary volcanic sequence. The Chilliwack batholith of quartz diorite and granodiorite straddles the International Boundary, extending north into British Columbia and south into Washington (Misch, 1966, p. 140-141). It was emplaced during several episodes; the oldest cuts the Paleocene Chuckanut Formation but not the overlying Oligocene volcanics, and the youngest cuts the Oligocene volcanics themselves. The younger phases have yielded radiometric ages of 30-18 m.y. Farther south in the Cascade Range are the batholith of Snoqualmie Granodiorite (Smith and Calkins, 1906), and the smaller Tatoosh batholith of similar composition in the Mount Rainier area (Fiske and others, 1963). Both lie mainly in the lower and upper Tertiary andesites and were emplaced during Miocene time. They rose to high levels in the crust, and late in their histories were explosively unroofed, giving rise to andesite flows, such as those in the upper part of the Keechelus Formation of the Snoqualmie area. Smaller intrusive bodies of similar character occur farther south in the andesites of the Cascade Range in Washington and Oregon.

OREGON COAST RANGE

In the Coast Range of Oregon, mafic intrusives are associated with the Eocene pillow basalts and the surrounding sediments. Although they occupy relatively large areas on the Geologic Map, they are merely thick sills.

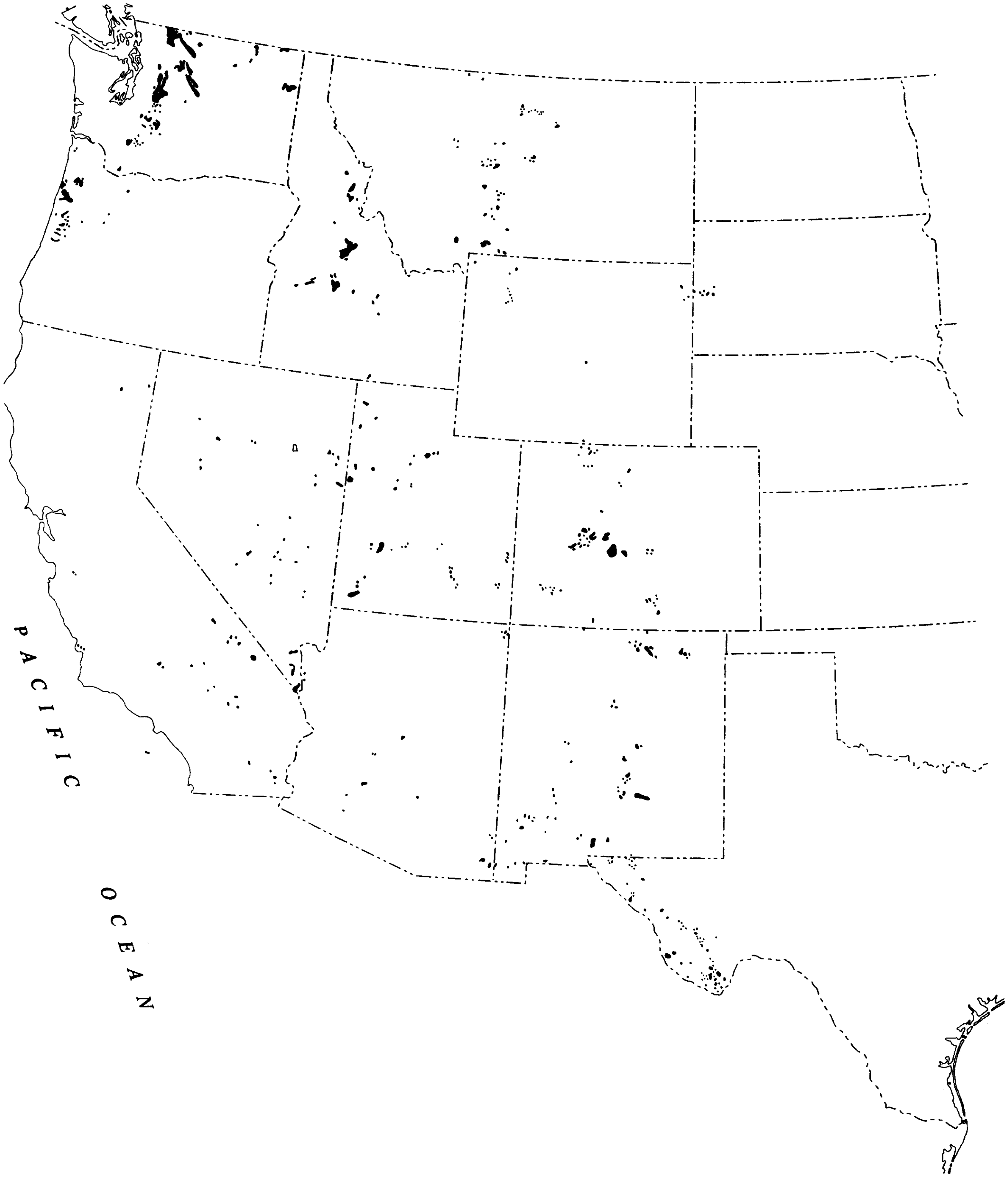

FIGURE 16.—Map of western United States showing distribution of Tertiary intrusive rocks as represented on Geologic Map of the United States (unit Ti).

CENTRAL IDAHO

In central Idaho to the east, the great Idaho batholith was the scene of long-continued plutonic activity that culminated during the Cretaceous, but lesser intrusive activity persisted into the early Tertiary, giving rise to several sizeable plutons embedded in the older complex. One of the larger bodies is in the Casto area of the central part of the batholith, where a mass of granite and quartz monzonite intrudes the Eocene Challis Volcanics (Ross, 1934, p. 54-67). A radiometric age of 59 m.y. is reported from it. Another somewhat smaller body of quartz monzonite, nearly surrounded by Cretaceous plutonic rocks, forms the Sawtooth Range farther southwest (Reid, 1963, p. 14).

CENTRAL MONTANA

To the east in Montana, east of the front of the Northern Rocky Mountains, numerous near-surface stocks, laccoliths, and satellitic dikes occur in the Crazy Mountains, Castle Mountains, Little Belt Mountains, Highwood Mountains, Bearpaw Mountains, Little Rocky Mountains, and Sweetgrass Hills (Larsen, 1940). In a few places, effusive equivalents are preserved. The igneous rocks range in composition from ordinary rhyolites, andesites, and syenites, to strongly alkalic rocks rich in potash and soda—shonkinite, nepheline syenite, and phonolite, almost devoid of plagioclase—with considerable variation from one area to another. The igneous rocks are generally considered to be Eocene.

CALIFORNIA AND GREAT BASIN

In California and western Nevada, plutonic activity virtually ended during Mesozoic time, except for a few widely spaced small Tertiary stocks. From central Nevada eastward in the Great Basin, however, Tertiary intrusive bodies are mingled with those of Mesozoic age and finally dominate at its east edge. They include the small intrusions of the northern Shoshone Range, with a lead-alpha age of 50 m.y. (Gilluly and Gates, 1965, p. 60), the larger Harrison Pass pluton of the Ruby Range, Nevada (Coats and others, 1965), and the Almo pluton of the Albion Range, southern Idaho (Armstrong, 1968, p. 1305), with Rb/Sr ages of 35 and 30 m.y., respectively.

At the east edge of the Great Basin, in the Wasatch Mountains southeast of Salt Lake City, a cluster of large stocks of quartz diorite and quartz monzonite lie on the western prolongation of the Uinta Mountains axis (Crittenden and others, 1973). The large Little Cottonwood stock rises at the mountain front; the smaller Alta and Clayton Peak stocks lie within the mountains to the east. Fission-track and K/Ar dating indicate that the stocks are progressively younger from east to west—the Clayton Peak being 37-41 m.y. old (late Eocene), the Alta 32-33 m.y. old (early Oligocene), and the little Cottonwood 24-31 m.y. old (early Miocene).

COLORADO PLATEAU

The Colorado Plateau east of the Great Basin is not notably an igneous area, except for the volcanic fields along its southwest and south edges. Within the plateau itself, a wide region is without igneous rocks, except for laccoliths in a few clusters—in the Henry Mountains, the La Sal Mountains, the Abajo Mountains, and the Carrizo Mountains. The Henry Mountains laccoliths, made famous by the pioneer work of G. K. Gilbert, have yielded Eocene K/Ar ages of 44-46 m.y.; the La Sal Mountains laccoliths are late Oligocene, with ages of 23-26 m.y. (Armstrong, 1969, p. 2085).

SOUTHERN ROCKY MOUNTAINS

The Sawatch Range and the Elk Mountains to the west, in the Southern Rocky Mountains of central Colorado, contain the only other area in the western United States besides those of the Northwestern States of truly deep-seated plutonic rocks of Tertiary age. These culminate in the large Mount Princeton pluton of the southern Sawatch Range, which has been dated radiometrically as late Eocene or early Oligocene. The Snowmass and Whiterock granodiorite plutons and others in the Elk Mountains are apparently somewhat younger, with Oligocene ages of about 34 m.y., and the Treasure Mountain pluton has a Miocene age of 12 m.y. (Obradovich and others, 1969).

These plutons all form part of the Colorado Mineral Belt, which contains numerous intrusions from the Front Range on the northeast, southwestward into the San Juan Mountains. Those in the Front Range are mainly Late Cretaceous, or "Laramide" (Kg4), those farther west are Tertiary. They lie within a series of pronounced gravity lows which suggest the presence of a large subjacent batholith, or batholithic complexes, of which the visible intrusive bodies are cupolas (Steven, 1975, p. 88-91). The plutonic rocks of the Southern Rocky Mountains are of interest because, unlike those farther west, they invade a rather thin sedimentary cover over a Precambrian basement; they must have risen through the Precambrian from a source in the underlying mantle.

SOUTHEASTERN BASIN AND RANGE PROVINCE

In southern Arizona the ages of the plutonic rocks become progressively younger eastward from mid-Mesozoic to dominantly Late Cretaceous ("Laramide") (Kg4), into southern New Mexico where all the intrusive rocks are early Tertiary. Most of these form relatively small stocks, but a larger pluton occurs in the Organ Mountains east of Las Cruces, and there are others in the Sierra Blanca and in Capitan Mountain farther northeast. In the trans-Pecos area of Texas to the south are numerous stocks, sills, and laccoliths, at least partly related to the early Tertiary volcanic activity; they are notable for their highly alkalic composition (Maxwell and others, 1967, p. 172–175). Similar alkalic intrusions extend northward from the trans-Pecos volcanic area as far as the Cornudas Mountains on the Texas-New Mexico boundary.

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