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AN OUTLINE OF THE STRUCTURAL GEOLOGY OF THE UNITED STATES

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AN OUTLINE OF THE STRUCTURAL GEOLOGY OF THE UNITED STATES

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AN OUTLINE OF THE STRUCTURAL GEOLOGY OF THE UNITED STATES

By Philip B. King

INTRODUCTION

This paper outlines the known structural features of the continental United States, with the exception of the Territory of Alaska. The structural features are grouped systematically into broad tectonic units, and the possible relations between features of different areas are suggested. The description includes an account of the geologic history of each region as recorded by the stratigraphy and discusses its relation to the diastrophism. The interpretations of the regional relations and history of the structural features are those which the writer considers best founded in existing evidence. Some of them are widely accepted, but others are not agreed on by all geologists. It is not possible in a short paper of this kind to review controversial questions in detail. The writer has therefore taken the liberty of giving the interpretations preferred by him personally, although some of them do not represent the consensus of opinion of American geologists. He has endeavored, however, to make the accompanying bibliography sufficiently complete to include ample reference to papers giving different interpretations.

The preparation of the paper has been made possible through the aid of the staff of the United States Geological Survey, who have criticized the manuscript, have given summaries of existing information, and have made available a considerable body of material not yet published. A brief bibliography is included, and the outstanding contributions of unpublished material are acknowledged in their appropriate places. It has not been possible, however, to acknowledge all the published and unpublished sources from which the paper has been compiled. For additional sources the reader is referred to references contained in various papers in the bibliography, to the other guidebooks of this series, and to the numerous folios of the Geologic Atlas of the United States.

Geographic features.—The United States includes a variety of geographic and tectonic units. Its interior consists of wide plains and low plateaus. Along its east side rise the low ridges of the Appalachians; on the west the diverse and rugged Cordillera forms a belt of mountain ranges a thousand miles (1,600 kilometers) in width. The low shores of the Gulf coast and of the Atlantic coast south of New England are bordered by gently sloping coastal plains, but the Pacific shore is rugged and abrupt and is flanked by a chain of Coast Ranges.

Relation between geographic and tectonic features.—There is a broad relation between the topography and the structure of the rocks beneath. Recent uplifts to a certain extent coincide with areas of former movement and disturbance. Streams, wearing away the soft rocks and leaving the hard, have produced contrasting land forms in areas of flat-lying and of folded strata. The lowland areas of the interior are thus underlain by rocks that have not been conspicuously folded. Most of the mountain areas are underlain by folded and faulted rocks, though the movements that deformed them were in general earlier than those which raised the present ranges.

Central stable region.—The interior plains of the continent have been a stable region for a long period of geologic time. In the central part of this stable region pre-Cambrian rocks are exposed over a vast area known as the Laurentian shield (2,[1] pp. 84–85). This area occupies the greater part of central and northern Canada and extends a short distance into the United States. Its ancient rocks are strongly folded and metamorphosed, but the forces that caused their deformation ceased to be active before Paleozoic time, leaving the rocks strong and rigid and thus competent to resist later forces of compression. South of the Laurentian shield, in the central United States, the basement rocks are thinly covered by Paleozoic and Mesozoic strata that have been flexed into gentle domes and basins (3, p. 165).

Geosynclines.—On the east, south, and west sides of the stable region are belts of greater mobility, which have been the sites of post-Algonkian orogeny. During the earlier phases of their history these belts have subsided as geosynclines and have received thick accumulations of Paleozoic and later sediments (3, pp. 170–192). Most of the mobile belts assumed a geosynclinal character as far back as the beginning of Paleozoic time, but they have had different later histories. Those on the east and south were filled by thick deposits of strata during the Paleozoic era and were strongly folded before the end of that era. In the western belt the orogenic events have been more complex. In places this belt received thick Paleozoic deposits, which were in part uplifted and even folded before Mesozoic time, but some wide areas were very little disturbed during the Paleozoic era. The greatest orogenic activity in the western mobile belt began in middle Mesozoic time and has continued through the Cenozoic.

[1] Numbers in parentheses refer to bibliography, pp. 54–57.

Border lands.—Along the margins of the mobile belts, away from the central stable region, were other positive areas of ancient crystalline rocks. These were the border lands which fringed the oceanward sides of ancient North America (3, pp. 158–163). In contrast to the Laurentian shield, which has had a passive history since Algonkian time, these areas have been extremely active and have had a constant tendency toward uplift. Great volumes of sediment eroded from their upraised parts have been deposited in the geosynclines. During the periods of compression they have behaved as hinterlands to the mobile belts. The rocks of the geosynclinal belts were overturned and thrust from the border lands toward the central stable region, which acted as a foreland during the movements.[2]

During their active history the border lands were sliced and broken and were injected with igneous rocks. Those on the eastern and southern borders are now quiescent, having subsided to such an extent that parts of their truncated surfaces have been buried beneath gently tilted Mesozoic and Tertiary coastal-plain deposits, and other parts have disappeared beneath the sea.

The border land that lay southeast of the geosyncline of the eastern United States is known as Appalachia; another one on the south is known as Llanoria. Along the west coast, beyond the western geosynclines, were other border lands, the largest of which is known as Cascadia.

PALEOZOIC STRUCTURAL FEATURES OF THE EASTERN AND SOUTHERN UNITED STATES

GENERAL FEATURES

Geographic character.—On the east and south sides of the central stable region of North America the rocks were strongly folded and faulted by Paleozoic movements and in places form low mountain ridges. Folds and faults of this age are found in the Appalachian Mountains, which extend along the eastern border of the United States from southeastern Canada to Alabama. West of the Mississippi are similar but disconnected groups of ridges in the Ouachita, Arbuckle, and Wichita Mountains of Arkansas and Oklahoma. In western Texas is the still more isolated mountain group of the Marathon region.

Throughout the region there has been no folding since Paleozoic time, and the lofty mountain chains of that era have been profoundly eroded. The present mountain groups result from the

[2] Cf. Collet, L. W., Structure of the Alps, p. 7, London, 1927.

differential erosion of the areas of folded rock after late broad uplifts. While these uplifts were being formed, large areas in the ancient mountain system subsided, and in consequence wide tracts are buried beneath coastal-plain deposits of Mesozoic and Cenozoic age.

Structural pattern.—The area affected by Paleozoic deformation [3] is much larger than that of the present ridges (12, p. 312). In the Appalachian region the crystalline rocks of the inner part of the system are worn down to the rolling hills of the Piedmont Plateau and the New England Upland. Their southeastern margin is hidden by the younger deposits of the Coastal Plain. Toward the southwest, also, the entire belt of deformed rocks strikes beneath younger strata and is hidden from view across the Mississippi embayment. West of the Mississippi only small segments of the belt are exposed at the surface. Most of its area is covered by strata of Cretaceous age, but the extent and trend of many of its structural features have been made known by drilling.

The strongly folded belt is long and sinuous and trends northeast and southwest across the eastern United States. It lies on the site of a Paleozoic geosyncline. The belt swings in great curves around structural salients which face toward the northwest (12, pp. 313–314). These salients appear to have been the centers of most active deformation. The Appalachian region contains three salients or arcs, whose chords are each about 400 miles (640 kilometers) long. West of the Mississippi are two other salients of strongly arcuate plan. The Ouachita Mountains form the apex of one, and the mountains at Marathon, Texas, the other.

Cross section of the deformed area.—The folds and faults of the deformed belt from New England to Texas persist for long distances along the strike, so that all segments of the system show a great similarity of cross section. The outer folds on the northwest are broad and open, but the intensity of the deformation increases inward across the strike. The inner folds on the southeast are high and tightly compressed, and most of them are overturned northwestward. There is also an increase in the metamorphism of the rocks toward the southeast (12, p. 315). In some places the outer part of the folded belt is marked by the traces of overthrust faults, along which the rocks of the geosyncline have been pushed toward the northwest, but elsewhere the

[3] Areas in which the rocks are strongly folded and faulted, rather than gently tilted, are called deformed or folded belts in this paper. These areas have generally been the sites of geosynclinal deposition in the past and have undergone one or more orogenic movements, so that during part of their history they have also been mobile belts. Those portions of the geosynclines or deformed belts which lie toward the foreland are called the outer parts, and those which lie toward the hinterland the inner parts.

strong deformation ends in this direction by the gradual diminution of the folds. In the southeastern part of the folded belt Paleozoic strata laid down in the inner part of the geosyncline, now in part metamorphosed, are thrust over the outer zones. These inner parts are in turn overridden by great thrust sheets of pre-Cambrian rocks of the hinterland. Within the hinterland batholithic masses of granite, not conspicuously sheared or distorted, invade the old rocks and are probably a late feature in the orogenic epoch (12, pp. 321–322).

Time of movement.—The Appalachian geosyncline from which the Paleozoic folds were produced had its inception in Lower Cambrian time. During the Paleozoic it received as much as 40,000 feet (12,000 meters) of sediments. These were chiefly derived at first from the border land of Appalachia, but later on they came partly from the older folds within the geosynclinal area. The region was the scene of deformation during several epochs in the Paleozoic era.

The northern Appalachians,[4] from the Maritime Provinces of Canada southward to Pennsylvania, were folded in Carboniferous time, but the record of considerably older movements is also clear. Along the west side of the deformed belt and extending into the foreland area are thick clastic deposits of Silurian and Devonian age, derived from the erosion of folds produced during the earlier movements. These strata were deformed by late Paleozoic movements, but they overlap more steeply inclined early Paleozoic rocks toward the east. In the northern Appalachians two movements of early Paleozoic age are recognized—the Taconian, at the end of the Ordovician period, and the Acadian, at the end of the Devonian period (24, pp. 323–325). In the inner part of the area of deformed rocks, in the northern Appalachians, are folded strata of Carboniferous age.

The central and southern Appalachians show little deformation before Carboniferous time. The middle Paleozoic clastic deposits in the outer part of the folded belt thin out southwestward along the strike, toward Alabama. The foreland areas of the southern region are covered by thick clastic rocks of Carboniferous age, derived from the erosion of uplifted areas to the southeast. These suggest notable deformation in the southern Appalachians. Along the northwestern flank of the deformed area Permian beds are folded equally with the earlier Carboniferous beds and indi-

[4] The term "Appalachians," as used in this paper, covers approximately the same area as Fenneman's geomorphic province the "Appalachian Highlands" (Physiographic divisions of the United States: Assoc. Am. Geographers Annals, vol. 18, pp. 261–353, 1928), though by popular usage the ridges north of Pennsylvania are seldom included in the Appalachian Mountains. Structurally, the region may be conveniently divided into two parts—a northern part and a central and southern part, with the line of division in northeastern Pennsylvania.

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cate the persistence of movements in the region until late Paleozoic time.

The strongly deformed Paleozoic rocks in the Appalachians are overlain unconformably by various Mesozoic deposits, the oldest of which are of Triassic age. The Triassic beds are not folded but are tilted and transected by large normal faults.

West of the Mississippi River the times of noteworthy movements were similar to those in the southern Appalachians. There is in the western region, however, a more complete record of the structural history, for the deformed area contains wide exposures of the later Paleozoic strata. The Wichita Mountain system, an outer branch of the folded belt, shows strong late Mississippian movements. Along the northwest side of the deformed belt, as in the southern Appalachians, there are thick clastic deposits of Carboniferous age, which indicate pronounced movements during the period in this region as well. The folds west of the Mississippi are in places overlain unconformably by gently tilted strata of Permian age, but there is evidence of slight recurrent movement until the end of Paleozoic time.

APPALACHIAN FORELAND

The folded belt of the Appalachian province is bordered on the northwest by a region of gently flexed Paleozoic rocks. This is the margin of the central stable region of North America and was the foreland of the Appalachian deformation; toward it the sedimentary rocks of the deformed belt are thrust and overturned (12, pp. 322–323). The gently folded rocks of the region stand in broad, level-topped plateaus, now deeply dissected, which contrast strongly with the sharp ridges and longitudinal valleys carved in the folded and overthrust strata.

Early Paleozoic stratigraphy.—The oldest rocks of the foreland are exposed in its northern part. Pre-Cambrian igneous rocks and metamorphosed sediments are exposed in the Adirondack dome of New York and the Laurentian Highlands of Quebec. In the Adirondacks these rocks are directly overlain by thin Upper Cambrian sandstones and limestones, although great thicknesses of older Cambrian strata were laid down in the geosyncline to the east. Farther north, in the Laurentian Highlands, Middle Ordovician strata rest directly on the ancient rocks. The Cambrian of the Adirondack dome is overlain by a few thousand feet of Lower and Middle Ordovician limestones (Beekmantown, Chazy, and Trenton) (8, pp. 32–48), which are also revealed in the Nashville dome, northeast of the southern Appalachians, in Tennessee.

Middle Paleozoic stratigraphy.—In the northern foreland area the rocks of Upper Ordovician to Upper Devonian age show a strong clastic development, with the coarsest and thickest materials toward the geosyncline to the southeast. To the northwest the deposits thin out across the foreland, and at a distance of several hundred miles from the edge of the folded belt they change gradually into shales and calcareous strata.

Shales and sandy shales of Upper Ordovician age overlie the Middle Ordovician limestones on the flanks of the Adirondacks and pass eastward into sandstones. In eastern Pennsylvania and southeastern New York the succeeding early Silurian beds consist of sandstones and conglomerates, which are overlain by red shales. The overlying Devonian sandstones and shales, with subordinate limestone layers, pass upward into a great mass of coarse sandstones, of continental origin (Catskill, Oneonta), which thin out toward western New York and grade into marine shales (Chemung and Portage). There is a marked discordance between the Ordovician and Silurian; in eastern New York the nearly horizontal Silurian and Devonian overlie tilted older rocks, though the break gradually dies out toward the southwest and is not found beyond central Pennsylvania. In this direction also the rocks of the two higher systems are themselves involved in later movements and are extensively exposed within the folded belt (27, p. 636). Southwest of Pennsylvania the middle Paleozoic deposits gradually thin, and in Alabama they are not more than 1,000 feet (305 meters) thick (4, pp. 119–158).

The clastic rocks of this group were derived from the erosion of uplifts and folds to the east, within the deformed belt of the northern Appalachians (24, p. 322). These folds appear to die out toward the southwest, along the strike of the Appalachians, for the thick deposits disappear in this direction. The coarse clastic rocks fall into two groups, one of Ordovician and Silurian age, the other of Upper Devonian age. These groups are probably related to two epochs of deformation observed within the deformed belt, the Taconian and Acadian disturbances.

Upper Paleozoic stratigraphy.—In northern Pennsylvania rocks of Carboniferous age overlie the Devonian and extend southwestward as far as Alabama in an extensive area northwest of the folded belt. In the foreland of Alabama and Tennessee the Mississippian consists of limestones as much as 2,000 feet (610 meters) thick, which pass into shales and sandstones of greater thickness toward the southeast. The Pennsylvanian, which is largely clastic and coal bearing, is generally a few thousand feet thick in the foreland but increases to 5,000 feet (1,500 meters) in the outer folds of the deformed belt in Pennsylvania, and to 10,000 feet (3,050 meters) in those of Alabama (4, p. 208).

Northwest of the close folds, in Pennsylvania and West Virginia, the Pennsylvanian is overlain by sandstones and shales of Permian age, which are deformed equally with the underlying rocks in the broad outer folds of the region.

The clastic deposits of Carboniferous age in the foreland of the southern Appalachians indicate that strong movements took place during this period within the geosyncline or hinterland. During Carboniferous time the scene of pronounced activity in the Appalachian region shifted to the southwest of the position which it had occupied in previous periods, and the thickest Carboniferous deposits are found in Alabama, where the middle Paleozoic clastic rocks are thin. The relations of the Pennsylvanian and Permian in the outer folds indicate that at least a part of the deformation continued until late Paleozoic time, but it is not possible within the closely folded belt to determine how many of the structural features are older or younger than the Permian.

Structural features.—The folded belt of the Appalachians, as far north as Pennsylvania, is flanked on the northwest by the rugged and deeply dissected Cumberland and Allegheny Plateaus. These are underlain by gently flexed Carboniferous strata, which lie in a broad basin elongated parallel to the strike of the folds to the southeast (21, figs. 2 and 3). Northwest of the basin are the Nashville and Cincinnati domes, in which some of the older rocks of the foreland are laid bare by erosion.

Northeast of the Allegheny Plateau the Carboniferous rocks have been eroded from the foreland area and the strata rise gradually toward the Adirondack dome of northern New York, laying bare successively older formations of the Paleozoic. In northern Pennsylvania and southern New York are plateaus of Devonian clastic rocks. They reach their greatest prominence in the Catskill Mountains, which rise west of the Hudson River with steep escarpments in front of the folded belt.

In the Adirondack dome of northern New York a broad area of pre-Cambrian rocks is laid bare, surrounded by tilted Cambrian and Ordovician rocks. The eastern edge of the dome is near the front of the folded belt, but its rocks are not conspicuously deformed. They are traversed by a few large normal faults. (8, pp. 53–55.)

NORTHERN APPALACHIANS

The northern Appalachians extend from Pennsylvania northeastward into Canada. In eastern New York the front of the folded belt lies along the Hudson Valley. Farther north it follows the east shore of Lake Champlain and the south shore of the Gulf of St. Lawrence. The inner part of the area of deformation, composed of igneous and metamorphic rocks, has been worn down to a rugged upland, which embraces most of New England.

The structure of the region is exceedingly complex. There have been several periods of deformation. The strata are greatly metamorphosed and have been invaded several times by igneous rocks. The outer margin of the deformed belt has been strongly overthrust against the foreland, where the Adirondack Mountains and Laurentian Highlands stood as resistant buttresses.

Early Paleozoic geosynclines and geanticlines.—The earlier Paleozoic rocks of the northern Appalachians were laid down in two parallel geosynclines (23, p. 703). The northwestern and larger geosyncline flanked the southeast margin of the Appalachian foreland and extended from western New England northeastward to the Gaspé Peninsula. The southeastern geosyncline extended from eastern New England northward into New Brunswick and Nova Scotia. These areas of sedimentation were separated in central New England by a geanticline of ancient crystalline rocks.

Stratigraphy of northwestern geosyncline.—In New York and western New England the northwestern geosyncline contains a thick succession of Cambrian and Ordovician rocks. These include strata of Lower Cambrian age, which were not deposited in the foreland to the west (1, fig. 8). In the western part of the geosyncline are thick formations of limestone and dolomite. Farther east the strata change to a clastic facies. Here the Cambrian consists of slates and grits, and the Ordovician of black graptolite slates (22, pp. 73–130).

In Canada the earlier Ordovician of the northwestern geosyncline is a thick succession of sandstone and graptolite shales ("Quebec group"). These are thrust against the foreland rocks. A limestone facies formerly present on the northwestern border of the geosyncline, such as occurs in New England, is no longer exposed here. Large and small transported fragments of Cambrian and Ordovician limestones embedded in the "Quebec group" indicate its former existence (23, p. 706). In Gaspé the Lower Ordovician is overlain by Middle Ordovician volcanic rocks, locally succeeded by late Ordovician shales and limestones. These rocks are overlain with marked structural discordance by Silurian and Devonian sandstones and limestones (23, p. 712).

Stratigraphy of the southeastern geosyncline.—The rocks of the southeastern geosyncline are most widely exposed in Maine, New Brunswick, and Nova Scotia. Here a thick succession extends from Cambrian to Devonian, with much volcanic material in the upper part. Farther south, in Massachusetts, where the pre-Cambrian is more widely exposed, the deposits of the southeastern geosyncline are represented by a few small areas of Cambrian slates. The faunas of the geosyncline are unlike those to the northwest and have their closest affinities with Europe.

In the southeastern part of the Maritime Provinces and New England there are extensive exposures of Carboniferous clastic rocks, mostly of continental origin. They overlie the older rocks with marked structural break. In Gaspé and New Brunswick they are flat-lying or gently tilted, but in Massachusetts and Rhode Island they have been considerably deformed (23, p. 708). No strata of this period are found along the northwest flank of the northern Appalachians.

Northwestern Vermont.—The western margin of the northern Appalachians is marked by the trace of great thrust faults which have carried Cambrian and Ordovician rocks of the geosyncline northwestward over foreland strata of the same age (23, pp. 711–712). In northwestern Vermont the frontal overthrust crops out along the eastern shore of Lake Champlain, not far from the eastern edge of the Adirondack dome. East of it is a lowland belt about 15 miles (24 kilometers) in width, underlain by greatly deformed strata, which is flanked farther east by the Green Mountains, made up of greatly metamorphosed rocks.

In the area between the frontal overthrust and the Green Mountains are two thrust sheets of Cambrian and Ordovician rocks of the geosyncline, broken by innumerable minor thrusts (13, fig. 1). The strata of the western sheet are markedly different from those in the foreland to the west, and the eastern sheet contains a sequence unlike the western. The succession on the west includes prominent slaty members, and that on the east a great thickness of limestone and dolomite (13, pp. 358–363).

The eastern sheet overlaps the western toward the south and hides it entirely from view in southern Vermont. It is in turn overridden by the pre-Cambrian metamorphic rocks of the Green Mountains.

Taconic Mountains.—In southwestern Vermont the Taconic Mountains rise abruptly from the lowland area east of Lake Champlain. They extend southward for 100 miles (160 kilometers) in a chain of ridges that lie west of and parallel to the Green Mountains. The two mountain areas are separated by a narrow strip of lowland, floored by Cambrian and Ordovician limestones, which at the north joins the Champlain lowlands.

The Taconic Mountains are capped by Cambrian and Ordovician grits and shales, now partly altered to slates and schists. These rocks form a great thrust sheet which rests on Cambrian and Ordovician limestones like those on the east side of the Champlain lowland. The sheet is folded into broad synclinoria, separated by anticlinoria in which the overridden limestones are revealed by erosion. In places later thrusting has caused an intercalation of the limestone with the overriding rocks. The rocks at the base of the thrust sheet have been profoundly altered by mylonitization (20).

West of the Taconic Mountains are several large overthrust faults. One of these is well exposed at Bald Mountain, north of Albany, where wedges of Ordovician limestone are dragged along the sole of the overriding block (8, pp. 108–109). Ordovician rocks are revealed in windows for several miles east of the front of these faults, by the erosion of Cambrian rocks on the thrust sheets (22, pp. 144–148).

The Taconic overthrust is separated by erosion from its roots to the east. Its rocks most closely resemble the Cambrian and Ordovician strata within the Green Mountains, and it is probable that they were once connected. The westward displacement of the overthrust mass may thus exceed 40 miles (64 kilometers).[5]

Hudson Valley.—West and south of the Taconic Mountains the lowlands of the Hudson Valley are underlain by steeply tilted Ordovician slates. To the southwest these pass unconformably beneath gently tilted late Silurian and Lower Devonian rocks in the Helderberg escarpment (22, p. 157). Similar relations can be observed at other places farther south along the Hudson River, but in exposures nearest to the deformed belt the strata above the unconformity are themselves broken by thrust faults (24, pp. 307–320).

In Pennsylvania and New Jersey thick sandstones and conglomerates of early Silurian age lie unconformably on Ordovician slates, but the discordance disappears gradually to the southwest along the strike (27, p. 630). The Silurian conglomerates overlap the Ordovician toward the east and in the New Jersey highlands lie directly on the pre-Cambrian (5, p. 21).

Eastern New England.—The schists and gneisses of the Green Mountains are the western border of a metamorphic complex which underlies most of the New England Upland. In places this complex is invaded by large masses of Paleozoic granite. Irregular zones of retrogressive metamorphism in the complex indicate obscurely the trace of overthrust faults (15, pp. 454–457).

East of the Green Mountain anticlinorium is a synclinorium in the upper Connecticut Valley which contains Paleozoic rocks as young as the Devonian. These are the easternmost deposits of the northwestern geosynclinal area (23, p. 716). To the east is another anticlinorium of pre-Cambrian rocks in the White Mountains, beyond which, in Maine, are wide areas of strongly folded Paleozoic rocks of the southeastern geosyncline.

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[5] Personal communication from Arthur Keith.

In Rhode Island and eastern Massachusetts Carboniferous clastic rocks are infolded in the complex. They lie unconformably on pre-Cambrian and early Paleozoic rocks and on pre-Carboniferous granites (6, pp. 97–98). The Carboniferous strata are strongly folded and faulted and in some places are invaded by younger granites.

Triassic areas.—In the northern Appalachians, in Nova Scotia, Connecticut, and central New Jersey, are rocks of Triassic age (Newark). They rest with great unconformity on the deformed and metamorphosed pre-Cambrian and Paleozoic rocks and consist of shales, sandstones, and arkoses of continental origin, with interbedded lava flows and some basic intrusives. They lie in basins that are transected and in part bounded by normal faults. The Triassic rocks of Connecticut are tilted toward the east, and those of New Jersey toward the west. Where the margins of the basins are bordered by faults, there are coarse conglomerates derived from the erosion of the adjoining regions, which probably stood as highlands at that time (16, pp. 231–236).

CENTRAL AND SOUTHERN APPALACHIANS

The central and southern Appalachians exhibit a more regular topographic and structural plan than the mountains farther north and have very similar cross sections from Pennsylvania to Alabama.

The mountains are divisible into several narrow parallel belts of similar topography and structure, which follow the trend of the range (4, pp. 43–47). On the northwest are the Cumberland and Allegheny Plateaus, underlain by gently tilted strata. Southeast of the plateaus are the Appalachian valleys and ridges, carved from steeply tilted Paleozoic rocks which form the outer part of the closely folded belt. Beyond are the mountains of the Blue Ridge province, underlain by pre-Cambrian and early Paleozoic rocks, which are flanked in turn by the lower country of the Piedmont Plateau, underlain by metamorphic and igneous rocks.

Valley and Ridge province.—The Paleozoic rocks of the Valley and Ridge province are much thicker than those to the northwest. The transition from a thick geosynclinal sequence to a thin foreland sequence may be traced in successive exposures of the younger formations, and though the older Paleozoic formations are widely concealed it is robable that a similar thinning takes place in them also (1, p. 342, fig. 11).

The early Paleozoic rocks of the province are chiefly limestones and dolomites, which in the Upper Cambrian and Lower

Ordovician form a mass 8,000 feet (2,400 meters) thick (4, pp. 61–117). The limestones are worn down into valleys and lowlands. The higher uplifts of the region reveal an underlying section of earlier Cambrian strata as much as 5,000 feet (1,500 meters) in thickness. A clastic facies of the early Paleozoic such as characterizes the inner part of the geosync inal belt in the northern Appalachians and in the Ouachita Mountains, to the west, is but slightly represented in this province; the only conspicuous noncalcareous rocks are sandstones and shales of the Lower Cambrian and locally developed graptolite shales of the Lower Ordovician (such as the Athens of Alabama). In Pennsylvania and Maryland a section like that in the Valley and Ridge province apparently extends across the Blue Ridge province to the southeastern border of the geosyncline (28, pp. 521–524). In this region formations in the higher Ordovician overlap the Lower Ordovician and the Cambrian, to the southeast, and rest directly on the pre-Cambrian in parts of the Piedmont province.

The Upper Ordovician, Silurian, and Devonian rocks are thick and predominantly clastic in the central Appalachians and are related to rocks of similar character in the foreland area in New York. They thin out along the strike toward the southwest and in Alabama form a subordinate element in the geosynclinal section (4, pp. 119–158).

Mississippian and Pennsylvanian rocks occupy synclinal remnants in the folded area. In Alabama the Mississippian limestones of the foreland change toward the southeast, in the geosyncline, into 5,000 feet (1,500 meters) of sandstones and shales (Floyd and Parkwood) (4, pp. 201–206). The Pennsylvanian in the synclinal areas in Alabama reaches 10,000 feet (3,050 meters) in thickness, although only the oldest division (Pottsville) is represented.

The folds of the Valley and Ridge province rise abruptly along the southeast flank of the Cumberland and Allegheny Plateaus. The rocks stand in sharp parallel anticlines and synclines, overturned toward the northwest. A few sharp anticlines (such as the Sequatchie, in Tennessee) bring up the older rocks northwest of the main folded belt. Many of the folds are broken on their overturned limbs by thrust faults. In parts of Virginia and Tennessee the rocks of the valley are thrust upon the Carboniferous rocks of the foreland in flat overthrust sheets. The overridden rocks are revealed here and there by the erosion of windows in the thrust masses. There are also extensive overthrusts within the folded belt, many of which were formed early in the deformative epoch and have since been folded.

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The folds of the Valley and Ridge province decrease in intensity northeast of Virginia. The large overthrusts and thrust faults which break the folds in that State continue no farther north than Maryland. In southern Pennsylvania, though the rocks of the province are steeply folded, large thrust faults are rare. The outer anticlines in Pennsylvania pitch northeast, flatten out along the strike, and merge into the Allegheny Plateau, where they are represented by gentle flexures in the Devonian and Carboniferous strata in northern Pennsylvania. This relation is well represented on the geologic map of the State.

Blue Ridge province.—In Pennsylvania, Maryland, and Virginia the Blue Ridge province, southeast of the Valley and Ridge province, is underlain by pre-Cambrian metamorphic rocks and by early Paleozoic strata, which are folded into an anticlinorium (9, p. 506). The anticlinorium is bounded on the northwest by a thrust fault by which its rocks are thrust over those of the Valley and Ridge province. The folds of the Blue Ridge province plunge northeast, and in southern Pennsylvania most of their area is occupied by outcrops of Paleozoic strata (9, p. 505).

In the southern part of the Appalachians the Valley and Ridge province is bounded on the southeast by thrust slices of partly metamorphosed and generally unfossiliferous rocks of sedimentary origin, some of which may represent Paleozoic deposits laid down in the inner part of the geosynclinal area. In the Great Smoky Mountains of eastern Tennessee one such sheet contains a great mass of clastic rocks, the greater part of which is classed as of Cambrian age. In Alabama a similar thrust sheet contains slate (Talladega) which has been variously assigned to the pre-Cambrian and to the Paleozoic. The stratigraphic succession in a portion of the slate as described by Butts (4, pp. 49–61) is in the author's opinion somewhat similar to that of the Paleozoic rocks of the Ouachita Mountains farther west and permits a suggestive comparison.

Piedmont Plateau.—The northern part of the Piedmont Plateau is separated from the Blue Ridge province by the Martic overthrust, by which the crystalline rocks of the Piedmont have been thrust northwest over those of the Blue Ridge province (10). The rocks at the base of the thrust sheet have been profoundly affected by retrogressive metamorphism (9, pp. 507–508). The Piedmont rocks are in part at least the sheared and deformed remnants of the borderland of Appalachia. Most of them are of pre-Cambrian age, though in some places in Virginia and Maryland the complex is overlain by infolded remnants of Cambrian and Ordovician quartzites and slates. In Pennsylvania and Maryland the pre-Cambrian consists of a succession of metamorphosed sedimentary rocks (Glenarm series), which lie unconformably on older gneisses (9, p. 505). The metamorphic rocks are invaded by large granitic bodies, some of which are little altered by deformative movements and are probably of late Carboniferous age (9, pp. 512–513; 12, pp. 321–322).

Post-Paleozoic structural features.—Triassic rocks similar to those farther north occur in depressed areas in the Piedmont Plateau as far south as South Carolina. Here, as in the northern districts, they are extensively broken by normal faults. Cretaceous rocks of the Coastal Plain rest unconformably on the folded and faulted rocks. They conceal the southeastern extension of the metamorphic rocks of the Piedmont Plateau and bury the southwestern extension of the folded belt in Alabama.

After Cretaceous time the Appalachian province was broadly uplifted by recurrent movements (12, p. 333). The Cretaceous and Tertiary rocks dip toward the Atlantic Coastal Plain on the southeast at low angles and also dip to the west, toward the Mississippi embayment, at the south end of the mountains (26, pp. 808–809). Residual erosion surfaces on the summits and slopes of the Appalachians indicate a pulsatory upward movement of the region and possibly gentle flexing, until relatively recent time.

STRUCTURE WEST OF THE MISSISSIPPI RIVER

The Appalachian folds in Alabama pass southwestward along the strike beneath Cretaceous coastal-plain deposits. On the opposite side of the broad downwarp of the Mississippi embayment, covered by younger rocks, are the Ouachita Mountains of Oklahoma and Arkansas. These lie considerably north of the projected southwestward strike of the Appalachians. The Ouachita Mountains have a structural arrangement like that in the Appalachians, but the folded belt is in a large part covered by Cretaceous rocks.

Southwest of the Ouachita Mountains a continuation of the folded belt is covered by younger rocks but has been traced through Texas by drilling. In western Texas folded rocks like those in the Ouachita Mountains reappear in the mountainous area near Marathon. These different folded areas appear to be parts of a single great mountain system comparable to the Appalachians and perhaps continuous with it.

Northwest of the folded belt of this system is a broad, gently flexed foreland area. This is broken near the west end of the Ouachita Mountains by a chain of sharp Paleozoic uplifts, which trend west-northwest through southwestern Oklahoma and northwestern Texas. Most of these uplifts are buried beneath younger rocks, but two higher areas still rise in the Wichita and Arbuckle Mountains.

Foreland areas.—North of the Ouachita Mountains early Paleozoic rocks are exposed in Missouri, northeastern Oklahoma, and northern Arkansas in the Ozark uplift. They consist of a moderate thickness of Cambrian and Ordovician limestones, which rest, with a basal sandstone, on a rugged surface of pre-Cambrian igneous rocks. Between the Ouachita and Ozark areas is the Arkansas Valley, a basin of early Pennsylvanian clastic and coal-bearing strata (30, pp. 92–93). Toward the south the series attains a thickness of 11,000 feet (3,350 meters) near the flanks of the Ouachita Mountains, but it thins to a fifth this figure 100 miles (160 kilometers) to the north. The rocks of the Arkansas Valley are thrown into broad folds for some distance north of the Ouachita Mountains.

In the foreland area of central Texas early Paleozoic rocks come to the surface in the uplift of the Llano and Burnet area (sometimes called the Central Mineral Region). Here, as in the Ozarks, are Cambrian and Ordovician limestones, resting with a basal sandstone on pre-Cambrian granites and schists (19, pp. 1062–1063). The folded belt in central Texas, now buried beneath the Cretaceous, is flanked on the west by thick early Pennsylvanian clastic rocks (7, pp. 9–11). In western Texas early Paleozoic foreland rocks are revealed several hundred miles northwest of Marathon, where they are thrown into broad folds of the same age as the Marathon deformation (14, p. 115).

Northwest of the deformed area, in western Oklahoma and Texas, are broad basins filled by Permian marine and continental deposits. These were laid down after the climax of the deformation in the region. They surround and partly bury the uplifts of the Wichita Mountains and overlap the main folded belt in western Texas. In western Texas, north of the Marathon folds, is a deep depositional basin, filled by Permian marine sediments. This is bordered on the north and east by thick limestone reef barriers (14, pp. 80–84). Northeast of the reefs, in the Llano Estacado, are thick layers of red beds and saline deposits which extend as far as the Wichita Mountains (30, pp. 79–85). Other basins of Permian red beds lie north of the Wichita Range.

Wichita and Arbuckle Mountains.—The rocks of the Wichita and Arbuckle Mountains are similar to those of the surrounding foreland but are exceptionally thick. The section includes such competent formations as the 5,000 feet (1,500 meters) of Arbuckle limestone (Cambrian and Ordovician) and is similar to that in the southern Appalachian Valley. The folds evidently rose from an intracontinental geosyncline of moderate depth.

The Wichita Mountains have been shown by drilling to be an exposed fragment of a more extensive system of en échelon folds (19, pp. 1056–1057). These extend from the area near the front of the Ouachita Mountains west-northwestward into northwestern Texas. Less definite evidence suggests that they continue beyond into Colorado, where they join Paleozoic folds of similar character in the eastern Rocky Mountains. The Wichita system was uplifted in late Mississippian time and is overlapped by the Pennsylvanian (29, pp. 20–24).

The Wichita folds near their east end are flanked on the north by the Arbuckle Mountains, a horstlike mass of early Paleozoic rocks, raised during Pennsylvanian time (30, pp. 23–26). Near these mountains the Pennsylvanian contains great marginal conglomerate deposits, and each formation overlaps the next lower toward the uplift (30, pp. 24–25). The upper formations of the Pennsylvanian rest on all the older formations down to the pre-Cambrian and are very little deformed (29, p. 51).

Ouachita Mountains.—The open folds of the Arkansas Valley change toward the south into complex, tightly compressed and faulted folds, whose rocks have been carved into the rugged ridges of the Ouachita Mountains.

The rocks of the Ouachita Mountains are of a markedly different facies from those in the foreland to the north or in the Arbuckle and Wichita Mountains to the west (19, p. 1036). The oldest strata are Cambrian, Ordovician, and Silurian black slates with some sandstone and chert members, overlain by ridge-making Devonian novaculite. This is succeeded by a vast succession (as much as 20,000 feet, or 6,000 meters) of sandstones and shales (Stanley, Jackfork, Caney, and Atoka) of late Mississippian and early Pennsylvanian age. These are the youngest rocks in the mountains and are older than the coal-bearing Pennsylvanian strata of the Arkansas Valley.

In Oklahoma the change from rocks of foreland facies to those of geosynclinal facies takes place abruptly along the traces of thrust faults at and near the margin of the mountain area. The great mass of late Mississippian clastic rocks is absent north of these faults (18, p. 25). Along the outer border of the Ouachita Mountains, a shale zone in the Carboniferous contains large exotic masses of early Paleozoic limestones of the foreland (18, p. 27). Within the mountains are exposures of several great overthrusts, with windows of overridden rocks revealed for several miles behind the front of the thrust sheets (18, p. 18). The overthrusts of Oklahoma are confined to the structural salient in that State and do not extend very far eastward into Arkansas. There is a gradual increase in the metamorphism of the rocks of the mountains toward the south, so that the shales of the outer folds are represented farther back by slates and phyllites.

To the south the roots of the Ouachita Mountains are masked by the Cretaceous overlap. The great mass of clastic rocks was eroded from highlands of crystalline rock in the region now concealed (17, pp. 76–77). This ancient land was a part of Llanoria and probably had much the same relation to the Ouachita Mountains as the crystalline rocks of the Piedmont had to the Appalachians.

At their west end the strike of the folds in the Ouachita Mountains bends to the southwest. The southwestward projection of the folds meets the buried southeastern extension of the Wichita folds at nearly right angles, and it is considered probable that rocks of the Ouachita facies are overthrust on those of the Wichita facies (19, p. 1034). As the folds of the Ouachita Mountains involve rocks of Pennsylvanian age, they are much younger than those of the Wichita system. It is probable that the Arbuckle Mountains were uplifted at about the time of the thrusting in the Ouachita Mountains and are a block of foreland rocks raised by northwestward pressure from the Ouachita area.

Relation of the Ouachita Mountains to the Appalachians.—There are many suggestive resemblances between the Ouachita Mountains and the southern Appalachians (30, p. 116). Both regions are strongly folded and faulted, and in both there has been thrusting to the northwest toward the central stable region and away from the hinterlands of crystalline rocks to the southeast. In both areas there is a thick development of early Pennsylvanian and late Mississippian clastic rocks derived from early uplifts to the south and southeast. However, the lower Paleozoic section of the Valley and Ridge province of the southern Appalachians finds its closest resemblance west of the Mississippi in the section of the Arbuckle and Wichita Mountains (30, p. 116). The predominantly clastic and cherty early Paleozoic rocks of the Ouachita Mountains have no definite counterpart farther east unless some of the metamorphosed rocks in the inner thrust sheets of Alabama are of Paleozoic age.

The actual connection between the two areas is hidden by the Cretaceous and Tertiary rocks of the Mississippi embayment. The folds of the Ouachita Mountains pass to the east beneath the embayment with a strike slightly south of east. The writer suggests that in the concealed area they may bend sharply southeastward to join the Appalachians in southern Alabama. At the present time neither deep drilling nor geophysical observations have produced very positive evidence for this interpretation. However, deep wells in central Mississippi, about halfway between the two areas, have penetrated steeply inclined Pennsylvanian sandstones below the Cretaceous.[6]

Southwestern extension of the Ouachita Mountains.—At their west end the Ouachita Mountains bend abruptly southward and

[6] Described in an unpublished paper by W. H. Monroe.

disappear beneath the Cretaceous. To the south, in Texas, the characteristic rocks of the mountains have been encountered in wells along a narrow belt as far as San Antonio (25, p. 820). West of the folded belt Paleozoic rocks of foreland facies are found below the Cretaceous, and east of it ancient schists, probably a part of Llanoria. Near San Antonio the folded belt swings abruptly to the west around the foreland mass of the Central Mineral Region and continues toward the Marathon region of western Texas.

Marathon region.—In western Texas folded rocks like those of the Ouachita Mountains are revealed by the erosion of a domed cover of Cretaceous strata. They occupy an area about 40 miles (64 kilometers) square. This is the Marathon region (30, pp. 63–76).

The stratigraphic section at Marathon is very similar to that in the Ouachita Mountains (14, p. 115). The Ordovician, although largely limestone rather than shale, contains the same graptolite faunas as in the Ouachita region. The Devonian is represented by a novaculite formation and is succeeded by thick sandstones and shales of late Mississippian and early Pennsylvanian age, like those in the Ouachita Mountains. Higher Pennsylvanian strata are infolded in the succession and contain conglomerates made up of fragments of the underlying rocks (14, p. 51). These conglomerates record the beginning of deformation in the region. The rocks of the Marathon area are intensely folded along a northeast strike and are broken by large overthrust faults. They are overlain unconformably by Permian marine deposits on the north, which are gently tilted away from the uplift (14, pp. 51–52).

The Marathon folds, like those in the Ouachita Mountains, appear to have been bounded on the south by the land mass of Llanoria, from which the sediments of their geosyncline were derived. Exposures of the ancient rocks of this land have been found beneath the Cretaceous at a few places not far south of Marathon, in northeastern Mexico (42, p. 133).

Post-Paleozoic structure.—The truncated Carboniferous folds are overlapped from the Gulf of Mexico by gently inclined Cretaceous and Tertiary coastal-plain deposits (17, pp. 78–79). In the valleys of the Mississippi River and the Rio Grande these strata reach a considerable thickness and are depressed in deep embayments (26, p. 890). Along the inner margin of the Coastal Plain in Texas is an extensive system of normal faults in the Cretaceous and Tertiary, the Balcones fault zone (26, p. 890). In this area, as well as in Arkansas, the Paleozoic and Cretaceous rocks are invaded by numerous plugs and necks of porphyritic igneous rock. To the west, near the Rio Grande, the Marathon folds are cut off by the younger structures of the Cordilleran system, and in Colorado the northwestern extension of the Wichita folds passes into the younger structures of the Rocky Mountains.

CENTRAL STABLE REGION

GENERAL FEATURES

Location.—Between the Appalachian Mountains on the east, the Ouachita and other mountains on the south, and the Cordilleras on the west is a broad area of plains and low plateaus, drained by the Mississippi River and its tributaries. The post-Algonkian rocks that cover most of its surface are little deformed. This is the southern part of the central stable region of North America (3, p. 164).

Stratigraphic features.—The marginal parts of the central stable region are depressed and are buried by deposits derived from the erosion of the border lands or the flanking mountain chains. Throughout most of the vast inner part south of the Laurentian shield the pre-Cambrian rocks are covered by a relatively small thickness of post-Algonkian strata. These are a complex of limestone and shale lenses, laid down during successive incursions of the sea from various directions. Most of the sediments of the interior were carried from the distant mountain chains and border lands on the margins of the continent. A smaller volume came from the low-lying Laurentian shield or from local uplifts farther south. In the eastern part of the stable region the surface rocks are mostly of Paleozoic age. In the western part Cretaceous and Tertiary rocks cover wide areas.

The southern edge of the Laurentian shield, with broad exposures of pre-Cambrian rocks, extends from Canada into Minnesota, Wisconsin, and Michigan. Farther south the old rocks project through the Paleozoic in such uplifts as the Sioux quartzite area of southwestern Minnesota, the Ozark uplift, and the central Mineral Region of Texas. To the southeast they are exposed in the Adirondack dome.

Structural features.—The post-Algonkian rocks of the region are gently flexed and folded and dip at low angles. In a few places they are cut by faults and in a very few places by igneous intrusions. There are broad domes and basins with a width of several hundred miles, on which are superimposed insignificant local folds. To the southwest, originally connected with the main stable region, are other rigid masses, including the broad Colorado Plateau, which are now partly broken and isolated by post-Paleozoic movements.

LAURENTIAN SHIELD

Location.—In Minnesota, Wisconsin, and Michigan, to the south and west of the Great Lakes, are broad exposures of pre-Cambrian rocks which are the southern edge of the still more extensive area of the Laurentian shield in Canada.

Pre-Cambrian structure.—A considerable part of the area consists of granites and gneisses of various ages, but there are extensive exposures of folded and metamorphosed sedimentary rocks of Algonkian age, partly infolded in the granites and partly intruded by them (38). The oldest rocks are the most intensively deformed and contain the greatest quantity of injected igneous material. The higher divisions, consisting of slates, quartzites, and marbles, with interbedded iron-bearing members, are considerably less deformed, and in places their folds are broad and open. The rocks of the highest series, the Keweenawan, consisting of copper-bearing flows, agglomerates, and clastic continental beds, are tilted and cut by normal faults but are not folded. The strike of all the variously deformed Algonkian rocks is east-northeast.

Relation to Paleozoic beds.—The whole pre-Cambrian succession is truncated by the basal Cambrian sandstones, which were laid down on a slightly irregular or rugged surface that has not been conspicuously deformed since. At some localities south of the main area of pre-Cambrian exposure, as near Baraboo, Wisconsin, conspicuous eminences on the eroded surface have been partly exhumed and project through the surrounding Paleozoic strata.

PALEOZOIC AREAS SOUTH OF THE LAURENTIAN SHIELD

Location.—The pre-Cambrian rocks of the Laurentian shield pitch west, south, and east beneath a thin cover of Paleozoic strata. These lie at the surface over most of the central United States, from the Appalachians westward beyond the Mississippi River.

Stratigraphy.—The earlier Paleozoic rocks of the region consist of various lenticular limestone formations of Ordovician to Mississippian age, with some layers of shale and sandstone. The Silurian and Devonian systems in the area contain abundant low-lying reef masses of coralline limestone, and the Mississippian is conspicuously a crinoidal limestone. In Indiana and Michigan, however, the Mississippian contains layers of shale and fine sandstone which appear to have been derived from the Laurentian shield, to the north. In parts of the region, particularly in Oklahoma, there is a well-marked unconformity at the base of the Mississippian.

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The Pennsylvanian overlies the older Paleozoic rocks in downwarped basins. Over most of the interior region it rests on older formations of various ages with strong unconformity. The Pennsylvanian sediments of the outer basins appear to have been derived from the erosion of uplifted parts of Appalachia and Llanoria, and perhaps in the upper part from the rising Appalachian and Ouachita folds. Toward these areas of uplift the series becomes more clastic, with more coal beds and continental deposits and fewer marine members. In Kansas and Nebraska, farthest from the zones of deformation, the series is almost entirely an alternation of thin layers of marine shale and limestone. The sediments in some of the interior basins of the Pennsylvanian may have come from the Laurentian shield.

Illinois and Michigan basins.—South of the uplifted pre-Cambrian area of Wisconsin is the Illinois basin of Pennsylvanian rocks (36, pl. 1). To the southwest are Pennsylvanian exposures at the north end of the midcontinent basin, and to the southeast the nearly circular Michigan basin with Pennsylvanian rocks in the center.

Cincinnati and Nashville domes.—Southeast of the Illinois and Michigan basins are the Cincinnati and Nashville domes, which occupy the central part of Tennessee, Kentucky, and Ohio (31, pp. 3–18). These domes are elongated parallel to the closely adjacent folds of the Appalachian Mountains. Ordovician limestones are revealed on their crests, and escarpments of younger rocks on the flanks. Close study of the formations along their margins indicates that they have undergone several recurrent movements during Paleozoic time.

The Cincinnati and Nashville domes are separated from the folded belt of the Appalachians on the southeast by the depressed areas of the Cumberland and Allegheny Plateaus, in which clastic rocks of Pennsylvanian age are preserved.

Ozark dome.—West of the Nashville dome, on the opposite side of the Mississippi River, is the very broad Ozark dome. This uplift occupies most of the southern half of Missouri and extends southward into Arkansas and Oklahoma. Its crest is a broad, nearly circular area of Cambrian and Ordovician limestones, surrounded by escarpments of Mississippian strata. In the east-central part knobs of pre-Cambrian igneous rocks project through the Cambrian and Ordovician. The pre-Cambrian surface had considerable relief, and the younger strata are deposited on it with strong initial dips (32, pp. 151–164). The Ozark dome has been uplifted during several successive periods of the Paleozoic era, so that there are marked erosional unconformities and overlaps in the Paleozoic section.

The margins of the Ozark dome have been broken in many places by normal faults (33, pp. 178–185). In Oklahoma a prominent system of fractures extends southwest, away from the uplift, but in Arkansas the arrangement is less systematic. In southeastern Missouri the faults trend southeast. East of the Ozark uplift, in southern Illinois and western Kentucky, the rocks are broken by a complex fault mosaic and are intruded by small mas es of igneous rock, probably of Cretaceous or Tertiary age. Earthquakes within historic times in this region show the present instability of the area.

The Ozark dome is bordered on the south by the coal basin of the Arkansas Valley, which separates it from the Ouachita Mountains. To the west the Mississippian and Pennsylvanian strata dip from the Ozark dome toward the midcontinent basin of Kansas and Oklahoma.

Midcontinent area.—The surface rocks of the midcontinent area consist of Pennsylvanian and Permian rocks which are tilted toward the west and which strike slightly east of north. The surface structural features consist of low anticlines and plunging noses and in Oklahoma of parallel north-south belts of en échelon faults. The faults have no great extension laterally or in depth and appear to be fractures over lines of weakness in the basement rocks, along which there was movement at the time of the Ouachita thrusting (35).

As a result of extensive drilling for oil, the underground configuration of most of the midcontinent region is now well known, and the drill has brought to light many unexpected features. The pre-Carboniferous strata by no means follow the regular westward dip of the overlying beds but in some places stand considerably above their anticipated positions (37, pp. 120–127). Along a narrow belt extending southward through Kansas into Oklahoma pre-Cambrian crystalline rocks rise in places within 500 feet (152 meters) of the surface along the buried Nemaha ridge. This probably joins the Sioux quartzite area of southeastern North Dakota on the north. It owes its height partly to pre-Cambrian and partly to middle Paleozoic movements.

The minor folds of the midcontinent region overlie such buried hills of pre-Cambrian and early Paleozoic rocks as are found along the Nemaha ridge. The inclination of the strata increases with depth. The folds are caused by original dips off the hills, by differential compaction around them, and by recurrent movements along the same lines of weakness that raised the hills (37, pp. 129–132).

GREAT PLAINS

The eastern edge of the Cordilleras is flanked by the Great Plains, a marginal basin of Cretaceous and Tertiary strata, superimposed on the Paleozoic strata just described. In Kansas and

Nebraska the Great Plains are a broad syncline with gentle westward dips on the east and strong eastward dips on the west, at the margin of the Rocky Mountains (34, pl. 58). In southeastern Colorado the Cretaceous strata rise in the broad Las Animas uplift, which lies on the southeastern continuation of the Wet Mountains. Pre-Cambrian rocks have been penetrated at shallow depth on the uplift, and it may be the surface reflection of a buried Paleozoic fold, which connects the folds of the Wichita system on the southeast with the old uplifts in the Rocky Mountains of Colorado.

Farther north, in western North and South Dakota and eastern Montana, is a broad irregular basin of gently flexed late Cretaceous and early Tertiary strata. The westward extensions of the basin lie between the outer ranges of the Cordilleras. Along the east side of this part of the Great Plains, where the Cretaceous overlaps the Sioux quartzite ridges and other pre-Cambrian areas, the formations are thin and calcareous. Toward the mountains to the west they attain thousands of feet in thickness and contain many clastic and nonmarine members.

CORDILLERAN SYSTEM OF THE WESTERN UNITED STATES

GENERAL FEATURES

Geographic character.—On the western flank of the central stable region of North America a complex of ranges folded and faulted in Mesozoic and early Tertiary time extends westward nearly to the Pacific coast in a belt of mountains 1,000 miles (1,600 kilometers) in width. This is the North American Cordillera. [7]

The Cordilleran system is composed of many diverse structural and geographic parts. Its highest members to-day, the Rocky Mountains on the east and the Sierra Nevada on the west, owe their present altitude to late Cenozoic uplifts. The central portions of the system were equally folded during the culmination of the orogeny, but here considerable tracts have been depressed rather than elevated by later movements. In this central part, in the Columbia Plateau, the deformed rocks are buried beneath

[7] An excellent synopsis of the history of terminology of the western mountains is given by Daly (47, pp. 22–25). Unified schemes of terminology, in part based on tectonic and in part on geographic criteria, have been proposed by Daly (47, pp. 22–25), by Ransome (69, pp. 289–295), and by Fenneman (Assoc. Am. Geographers Annals, vol. 18, pp. 261–353, 1928). In this paper the term "Cordilleran system" is used for all the western mountains from the Rocky Mountains to the Sierra Nevada. The Coast Ranges, which apparently possess unique structural features, are excluded.

extensive sheets of basaltic lava. Farther south, in the Great Basin and the mountain and desert region of Arizona and northern Mexico, they have been ruptured and dislocated by faults.

As the principal topographic features of the Cordilleran system have resulted for the most part from uplifts subsequent to the culmination of the deformation, some of the present ranges include only small parts of widely extended structural units, and others embrace several diverse structural types. The present Sierra Nevada is only a fragment of a system of similar structural features which extends along the entire west side of the Cordillera. The Rocky Mountains, which extend with more or less topographic continuity from the Canadian border southeastward to southern Colorado, consist in the south of the outer ranges of the Cordilleran system and in the north of its more complex inner part.

Comparison with the Appalachians.—Like the Appalachians, the Cordilleran system rose from a geosyncline lying between the central stable region and the margin of the continent. Its rocks are thrust away from the continental border and toward the stable region, or from west to east.

Compared with the structure of the Appalachians, which have a narrow belt of deformation and a uniformity of cross section in different segments of the range, the structural pattern of the western mountains is far from regular. The western region of deformed rocks is very broad and includes different areas of unlike history and competency, which show a great variety of structural features. The system includes areas that have had an almost continuous tectonic and volcanic history, as well as several broad geosynclines of greater or less antiquity and some level positive nuclei, resistant to compressive forces. Parts of the present ranges are reelevated members of Paleozoic mountain chains.

The confusion arising from the variety and complexity of the western mountains is increased by the small extent of the areas that have been studied in detail, and by the wide tracts that are concealed beneath Cenozoic lava flows and intermontane deposits.

Time of movement.—The later Mesozoic and early Cenozoic movements in the western mountains were long continued, and local areas show a number of distinct epochs of uplift and folding. The deformation reached its culmination at different times in different parts of the region. Toward the west the Sierra Nevada and related chains were chiefly deformed in middle Mesozoic time, and Cretaceous strata overlap the eroded surface of their western margins. The Rocky Mountains and other ranges on the eastern border were folded chiefly at the end of the Mesozoic era. Cretaceous and Eocene rocks in basins between the outer ranges and in the marginal areas of the Great Plains contain the record of an eventful structural history. Here the folded rocks of the mountains are overlapped by Eocene strata. In the area between the eastern and western borders the dating of the principal movements is not everywhere definite, though it is probable that both middle Mesozoic and late Mesozoic deformation took place in parts of the region (53, pp. 117–118).

Subdivisions.—The Sierra Nevada and the areas related to it show the most active tectonic history of all the mountains in the Cordilleran region. Their sedimentary succession through the Paleozoic and early Mesozoic is characteristically slaty and clastic, with large amounts of included volcanic material and one or more major structural breaks in the sequence. Their middle Mesozoic deformation was accompanied by the emplacement of granitic batholiths of vast extent.

East of the Sierra Nevada region, in the northern Rocky Mountains and part of the Great Basin, is a zone of Algonkian and Paleozoic geosynclinal rocks overlain in part by Mesozoic strata. Farther south, in Arizona, western Texas, and northern Mexico, are Mesozoic geosynclinal rocks. Both areas are strongly folded and overthrust toward the east. Near the Canadian boundary the marginal overthrusts directly face the Great Plains, and in eastern Mexico they flank the Gulf Coastal Plain. Between these northern and southern areas plateaus and outer ranges, in general broadly folded, lie between the overthrust zone and the plains.

In Utah and Arizona the Colorado Pleateau, a rigid area whose rocks are not conspicuously folded, projects southwestward as a resistant buttress into the deformed area of the Great Basin. The plateau is flanked on the northeast by the concentric arcs of the Colorado Rockies. These broad folds, modified in part by considerable overthrusting, have risen on the site of Paleozoic mountains similar to the Wichita system in Oklahoma. Farther north other broad folds separated by intermontane basins lie in front of the overthrust zone in Wyoming and Montana. Unlike the inner zone, which has been deformed by distantly derived forces from the west, the outer ranges appear to have been raised along lines of weakness in the basement rocks of the region. Some of the outer folds impinge at an oblique angle against the frontal folds and thrusts of the inner zone.

Igneous history.—In the Sierra Nevada region granitic batholiths of tremendous size were intruded during middle Mesozoic time. Smaller, younger batholiths invade the geosynclinal area to the east. In the Colorado Plateau and the outer ranges there are no large intrusions, but the rocks are cut by numerous stocks and laccoliths. Lava flows and tuffs, in general somewhat younger than the climax of the deformation, are widely distributed over the western mountain area. The largest tracts are along the margins of the Colorado Plateau, in the Columbia Plateau, and in the Snake River Plain.

OUTER RANGES OF THE CORDILLERA

General features.—The broad outer folds of the Cordillera extend from central Montana southward through Wyoming and Colorado to northern New Mexico. They form the southern part of the Rocky Mountains. The present mountains reach their greatest height in Colorado and rise with steep front from the Great Plains on the east. To the north they include numerous ridges which are separated by broad intermontane lowlands or embayments of the Great Plains. In Montana and Wyoming the outer ranges are bounded on the west by the zone of complex structure of the interior of the Cordillera. In Colorado they diverge to the southeast away from the inner zone, from which they are separated by the Colorado Pleateau.

Paleozoic stratigraphy.—The earlier Paleozoic rocks in the outer ranges are thin and of foreland facies. Thin sandstones of Cambrian age overlie an irregular surface of ancient schists and granites, or of late Algonkian sedimentary rocks similar to those of greater thickness in the geosyncline to the west. Limestones of Ordovician to Mississippian age reach a few thousand feet in thickness. In Montana and Wyoming they are overlain by as much as 1,000 feet (305 meters) of Pennsylvanian limestones and sandstones and by thin Permian red beds and phosphatic shales. In these States the Paleozoic section does not exceed 5,000 feet (1,500 meters) in thickness.

In Colorado the later Carboniferous strata pass into coarse-grained red clastic rocks which locally reach a thickness of 15,000 feet (4,600 meters) and which were derived from late Paleozoic ranges near the sites of the present mountains.

Mesozoic stratigraphy.—The succeeding Triassic and Jurassic strata are partly of continental origin and reach a few thousand feet in thickness at most. Over the Paleozoic uplifts they rest directly on the pre-Cambrian, although some of the old ridges were not buried until Cretaceous time (65, p. 87).

The Cretaceous system has a great clastic development which records the beginning of orogeny in the Cordilleran region. In southeastern Idaho, in the marginal part of the inner zone of the system, the lower part of the Cretaceous consists of 15,000 feet (4,600 meters) of clastic rocks, which indicate notable movements to the west. In western Wyoming and Colorado the Upper Cretaceous has a thickness of 25,000 feet (7,600 meters), more than half of which belongs to the lower part of the series. The lower beds contain thick sandstone and nonmarine members which thin and interfinger with marine shales to the east. Similar continental Cretaceous beds fringe the margin of the overthrust zone in Montana.

In eastern Colorado, in the Denver Basin, the Upper Cretaceous is 10,000 feet (3,050 meters) thick. In contrast to that of the western areas, the lower part of the series is thin and calcareous, and the greatest thicknesses are attained in the marine shales of the upper part of the series. The Cretaceous system dwindles to a few thousand feet in thickness in the Great Plains to the east.

Volcanic activity is indicated within the Cordillera during the Cretaceous period by widespread intercalated layers of bentonite. In the Crazy Mountains of Montana the upper part of the system intergrades with andesitic tuffs.

Eocene stratigraphy.—The unquestioned Cretaceous deposits are succeeded by clastic and continental strata—Lance (Eocene?) and Fort Union (Eocene) formations—which record the first decided movements in the outer ranges of the Cordillera. In western Wyoming there are local unconformities within the series near the flanks of the mountains. The deposits reach 12,000 feet (3,650 meters) in thickness in the Hanna Basin of central Wyoming. In the Big Horn Basin the Fort Union formation contains many beds of congolomerate whose cobbles are to be matched with pre-Cambrian quartzites in eastern Idaho rather than with the rocks from any of the near-by younger mountains (56, p. 543). In Montana the Lance and Fort Union formations are represented near the overthrust front by a thick series of andesitic tuff in the Crazy Mountains, although to the east they pass into thinner coal-bearing nonmarine shales. In intermontane valleys and along the flanks of the Colorado Rockies andesitic tuffs and granite arkoses of this age record the erosion of active folds along the axes of the present ranges (65, p. 92).

The top of the early Eocene formations is everywhere marked by a great unconformity, so that the succeeding Eocene continental beds (Wasatch, etc.) truncate the folded rocks beneath (56, p. 544). They were laid down in intermontane basins after the ranges had assumed much their present outlines. In some places the Wasatch overlaps the eroded trace of the faults in the mountains, but in others, notably northwestern Wyoming, it is overridden by thrust sheets.

Outer ranges in Montana.—Near the Canadian border the overthrust zone of the Cordillera faces directly on the Great Plains. Farther south it passes behind the broad outer folds of the Big Belt and Little Belt Mountains, roughly parallel to the ranges on the west, which are followed to the south by other mountains of similar structure.

East of the Little Belt Mountains is a group of broad uplifts, of which the highest are the Big Snowy Mountains. These have a west-northwest trend, which diverges considerably from that of the Rocky Mountains to the west. They consist of broad, horstlike tilted blocks bordered by steep monoclinal flexures, which are followed in places by belts of en échelon faults and by groups of small igneous intrusions. With little doubt the monoclines lie above faults in the basement rocks along which there was uplift and horizontal movement when the thrusts in the Rocky Mountains were in motion (70, p. 10).

Outer ranges in Wyoming and South Dakota.—The ranges in central and eastern Wyoming are broad uplifts that reveal pre-Cambrian rocks in their crests, overlain by remnant patches of gently folded Paleozoic strata and flanked by steeply tilted Paleozoic and Mesozoic rocks. The margins of the mountains are cut in places by steep thrust faults. The ranges are separated by broad intermontane depressions covered in their central parts by gently flexed Tertiary strata.

In northern Wyoming the Owl Creek and Big Horn Mountains rise from the plains and form a long chain, strongly arcuate to the east, in front of the Heart Mountain overthrust in the northwestern part of the State (56). A marginal conglomeratic facies of the Wasatch formation on the east flank of the Big Horn Mountains serves to date the uplift of the chain. Farther east, and separated from the Big Horn Mountains by a broad basin, is the more domelike Black Hills uplift, with a general northwest trend (50, fig. 6). The rocks of the northern part of the uplift are intruded by numerous laccoliths.

Southwest of the Owl Creek Mountains are the Wind River Mountains, of similar structure but of northwest trend. At their northwest end these mountains approach the overthrust zone of western Wyoming at an oblique angle.

Rocky Mountains in northern Colorado.—Southeast of the Wind River Mountains are the Laramie Mountains, which continue southward into the Front Range of Colorado and form another arcuate group of chains, facing northeast. Behind the Front Range are more or less continuous, parallel arcuate uplifts which include the Park Range, Sawatch Range, and other mountains in Colorado. Northwest of the Sawatch Range, but not continuous with it, are the Uinta Mountains, which assume a westward trend in their extension into Utah and impinge at right angles against the Wasatch Mountains on the edge of the overthrust zone to the west (44, p. 599). These chains bend around the rigid mass of the Colorado Plateau to the southwest of them (43, p. 28). At their south ends the rocks of the Front Range and the Wet Mountains pitch beneath the Great Plains. The east side of the Front Range and the north side of the Uinta Mountains are in places bordered by steep thrust faults. The west sides of the Sawatch Range and some of the mountains west of the Front Range are bounded in places by flat overthrusts by which Paleozoic and pre-Cambrian rocks are thrust southwest over Cretaceous strata.

The Front Range and the Wet Mountains, to the southwest of it, are reelevated members of Paleozoic chains, which were uplifted in late Mississippian time (65, p. 83). Their uplift coincides with that of the Wichita Mountains in Oklahoma, along whose northwest extension the mountains lie. The erosion products of these early ranges were distributed to the east and west to form the 4,000 feet (1,200 meters) of Pennsylvanian red arkoses and conglomerates now found on the flanks of the Front Range and the Wet Mountains. The northwestern members of this group of ranges, such as the Uinta Mountains, show no evidence of uplift before Cretaceous time.

Sangre de Cristo Mountains.—West of the Wet Mountains are the Sangre de Cristo Mountains in which pre-Cambrian and Paleozoic rocks are thrust northeast over Cretaceous and Tertiary strata.[8] Near the north end of the present mountain range the folds and faults bend to the west in an arc which passes around the north side of the San Juan Mountains. The northeastward thrusts of the Sangre de Cristo Mountains impinge at an oblique angle against the southwestward and westward thrusts of the Sawatch Range and are evidently a younger feature. Eocene rocks as young as the Wasatch formation are affected by the thrusting in the Sangre de Cristo Mountains. Toward the south, in New Mexico, the folds and faults of the range die out near Santa Fe, in plateaus of flat-lying strata (49, p. 272).

The Sangre de Cristo Mountains have been raised near the site of a Paleozoic mountain range. Along the margin of the present mountains are 12,000 feet (3,650 meters) of red sandstones and boulder conglomerates of late Pennsylvanian and early Permian age, derived from the erosion of granites on the crest of the Paleozoic chain (58, pp. 6–11). This uplift is younger than that of the late Mississippian range in the Wet Mountain region; it is probably of late Pennsylvanian age and thus nearly contemporaneous with the folding of the Ouachita and Arbuckle Mountains in Oklahoma.

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[8]This and other information on Colorado is based on recent work in the State by members of the U. S. Geological Survey. A more detailed discussion of the structural features of Colorado is presented by T. S. Lovering and W. S. Burbank in an unpublished paper, from which some of the facts here given are taken.

COLORADO PLATEAU

The Colorado Plateau is a broad, almost circular area of slightly deformed rocks, between the Rocky Mountains on the east and the Great Basin on the west. Around its margins are folded and faulted mountain ranges. The region has had a persistent positive history. It has shown a constant tendency toward uplift and has been covered by only moderate thicknesses of strata, which have in part been removed during successive periods of uplift and erosion. The inherently positive character of the plateau has made the region a nucleus resistant to deformation (43, p. 33). The folds of the Great Basin have been crowded against it from the west, and it has in turn been thrust against the mountains in Colorado, which bend around it.

Stratigraphy.—The Paleozoic rocks of the Plateau, which rest on an irregular or rugged pre-Cambrian floor, are only a few thousand feet thick (43, p. 32). At the Grand Canyon, where the section is 3,500 feet (1,070 meters) thick, the Cambrian, Mississippian, and Permian are represented and there are massive limestone beds near the middle and top. In other parts of the plateau Devonian and Pennsylvanian strata appear in the sequence. Northeast of the canyon the Permian rocks become increasingly clastic toward the Paleozoic uplifts in Colorado.

The Triassic and Jurassic strata of the plateau are nearly all nonmarine and reach 3,000 to 4,000 feet (900 to 1,200 meters) in thickness. They contain thick members of eolian sandstone. Cretaceous shales and sandstones reach 5,000 feet (1,500 meters) in thickness in parts of the plateau and grade southwestward into continental beds.

Eocene strata of the Wasatch and younger formations are found in the depressed areas of the Uinta and San Juan Basins, to the north and east. Thick sheets of lava of Miocene and younger age are spread over the eroded surface of the older rocks near the margins of the plateau, in Mogollon Mesa on the southeast, the San Juan Mountains on the northeast, and the High Plateaus of Utah on the northwest (43, p. 26).

Structure of the plateau.—The rocks of the Colorado Plateau are flat-lying or gently tilted. The area contains broad uplifts and basins, broken in places by normal faults or abrupt monoclinal flexures (48, pl. 52). Few of the uplifts are of sufficient height to reveal pre-Cambrian rocks except in the deeper canyons. Along the west side the broad uplifts of the plateau have a southeast or a north-south trend, parallel to adjacent ridges in the Great Basin. Along the east and north sides are the deep Uinta and San Juan Basins, filled by Eocene rocks. At least a part of these various folds are contemporaneous with the stronger folding of the ranges to the east and west. In places, as in the Henry Mountains, the sedimentary rocks are invaded by groups of laccolithic intrusive masses (55; 44, p. 622). To the west and south the plateau breaks off in steep escarpments, in part of fault origin, which overlook the ranges of the Great Basin and the mountain and desert country of southern Arizona. The raising of the scarps has in part been accomplished by late Tertiary and Quaternary movements. Within the plateau the Colorado River, rejuvenated by uplift, has carved the Grand Canyon.

Rio Grande Valley.—To the southeast the plateau breaks off into the block mountains of the Rio Grande Valley of New Mexico (69, p. 333). Here broad masses of pre-Cambrian rocks, overlain by undeformed Paleozoic and Mesozoic strata of the plateau facies, have been tilted by normal faulting (49, pp. 65–252). The ranges on the west slope toward the plateau; those on the east are tilted gently toward the Great Plains, thus suggesting a broad arch profoundly broken by faults along its crest. Toward the south the fault blocks of the Rio Grande Valley end against the strong folds and overthrusts of the Mexican region; to the north they approach the folds of the Sangre de Cristo Mountains, at the south end of the Colorado Rockies.

NORTHERN ROCKY MOUNTAINS

General features.—The northern Rocky Mountains form that segment of the inner zone of the Cordilleran system which extends from the Canadian border southward through Montana and Idaho into northern Utah. In general, the folds of the region strike northwest, but there are local trends in other directions. The outer overthrusts of the zone face the Great Plains near the Canadian border, but farther south the folds of the outer ranges lie in front of them. To the west the zone grades indefinitely into folds produced primarily in late Jurassic time.

Algonkian stratigraphy.—The main folded belt of the northern Rocky Mountains is made up of a great succession of rocks of geosynclinal facies (47, p. 47). In northern Montana the most conspicuous element is a group of late Algonkian sedimentary rocks (Belt series), which lie at the surface over most of the ranges. The series is composed chiefly of dark slates and argillites, with some layers of quartzite and limestone, and reaches 30,000 feet (9,000 meters) in thickness (73, p. 314). It thins to the east, and in the foreland area the Cambrian overlaps it to rest on older metamorphic rocks.

Paleozoic stratigraphy.—The Paleozoic rocks above the Belt series in the overthrust zone of western Montana are not greatly different from those in the foreland to the east; but in British

Columbia, to the north, the group attains a great thickness. In southeastern Idaho the Paleozoic rocks also have a geosynclinal facies; the section is 20,000 feet (6,000 meters) thick and lies at the surface over most of the deformed area (66, p. 48). In the eastern part of the district the section resembles that in the Great Basin to the south. It extends down to the Lower Cambrian and consists mostly of limestone. Farther west the strata change over into clastic rocks with black graptolite slates in the Ordovician and sandstones and conglomerates in the Carboniferous above (72, pp. 17–34).

Mesozoic stratigraphy.—Mesozoic rocks are found only along the outer margin of the overthrust zone and are well developed in western Wyoming and southeastern Idaho (66, p. 81). Triassic and Jurassic shales and limestones, with some sandstone members, reach 10,000 feet (3,050 meters) in thickness. In southeastern Idaho these beds are succeeded by 15,000 feet (4,600 meters) of early Cretaceous shales and conglomeratic sandstones, probably derived from regions of late Jurassic movement to the west. In southeastern Idaho the folded belt is overlapped unconformably by Eocene strata (Wasatch formation).

Lewis overthrust.—Near the Canadian border the geosynclinal rocks of the mountains are thrust east along the flat plane of the Lewis overthrust toward the Great Plains (73, p. 331). At the mountain front rocks of the Belt series overlie intensely deformed strata as young as Eocene (Fort Union) (66, p. 382). The trace of the thrust is frayed by erosion; and in front of it a few solitary peaks, such as Chief Mountain, consist of remnant masses of the older rocks resting on the younger, isolated from their roots by erosion. Toward the south the Lewis overthrust passes behind the front of the mountains, which are a complex group of thrust slices of Carboniferous and Cretaceous rocks. West of the Lewis overthrust the rocks of the Belt series lie in great folds broken in places by thrust faults.

Osburn fault.—South of the Lewis overthrust the Rocky Mountains are transected by a group of west-northwesterly cross faults, of which the most prominent is the Osburn fault of the Coeur d'Alene district (71, p. 602). This fault has been traced from Spokane, Washington, to Missoula, Montana—a distance of 150 miles (241 kilometers). The offset of folds and other structural features on opposite sides of it indicates a horizontal displacement of the northern block by 12 miles (19 kilometers) or more to the east (71, p. 603). The fault is probably a flaw, formed at the time of the advance of the Lewis and other thrusts at the mountain front. On the southeastern projection of the Osburn fault the deep-seated fault zones in the region of the Big Snowy Mountains have the same trend and are probably related features.

Southwestern Montana.—South of the system of cross fractures many of the folds and faults strike north-northeast or northeast, but with many confusing and opposing trends. In the Phillipsburg district, not far south of the Osburn fault, are extensive overthrusts of the Belt series east-southeastward across Paleozoic and Cretaceous rocks (45, pp. 18–19). The thrusts have been folded and cut by younger granitic masses. To the southeast, in the Three Forks district, Cambrian and Algonkian rocks have been thrust in a similar direction over younger strata on the Lombard overthrust. Between the Lombard and Phillipsburg thrusts, near the mining camp of Butte, is the Boulder batholith, a granitic body 70 miles (113 kilometers) in length, elongate north-northeast (62, pp. 260–261), generally regarded as of either late Cretaceous or early Eocene age.

West of this area, in central Idaho, the folded and faulted rocks are cut off by the granodiorite mass of the Idaho batholith, which is probably of late Jurassic age.

Southeastern Idaho and western Wyoming.—South of the Idaho batholith the Paleozoic rocks are thrown into southeastward-trending folds which are broken by large thrust faults. To the south the older rocks pitch beneath level basalt flows of late Cenozoic age in the Snake River Plain. The plain is a late Tertiary cross warp nearly 75 miles (121 kilometers) in width (39, p. 85). It extends irregularly east and west across southern Idaho. On its south side folded Paleozoic rocks reappear from beneath the lavas with the same southeasterly trend.

The outermost thrust sheet of this part of the northern Rocky Mountains is the Heart Mountain overthrust, which lies some distance east of the Snake River Plain in northwestern Wyoming. Paleozoic rocks of the Absaroka Mountains have been thrust eastward along its flat plane across Cretaceous and Eocene strata. East of the main trace of the thrust, by as much as 25 miles (40 kilometers), small remnant masses of Mississippian limestone rest on the Eocene (Wasatch formation) on the summits of isolated peaks in the Big Horn Basin (56, p. 547). Miocene volcanic rocks and breccias of the Absaroka Mountains rest unconformably on the eroded surface of the overthrust plate.

West and south of the Heart Mountain fault the rocks are thrown into narrow persistent folds, broken by closely spaced parallel thrust faults. Where the structures emerge from the Snake River Plain their strike is southeast, but farther south they turn to a more southerly course. The next major overthrusts southwest of the Heart Mountain fault are the Darby and Absaroka, on the western border of Wyoming, which have been traced with some interruptions for a distance of 200 miles (320 kilometers). The Absaroka fault is in places covered unconformably by the Wasatch formation; the youngest strata involved in its movement are of late Cretaceous age.

In southeastern Idaho, west of and parallel to the Absaroka fault, is an even greater fault, the Bannock overthrust, on which an overriding mass of Paleozoic and early Mesozoic strata has been pushed as much as 40 miles (64 kilometers) eastward across folded early Mesozoic and Cretaceous rocks (66, p. 158). The Bannock overthrust has been traced from the Snake River Plain southward into Utah for a distance of 200 miles (320 kilometers). The rocks of the overriding block are thrown into folds, which are truncated at their bases by the sole of the fault. The fault plane has been somewhat warped, so that the overridden rocks are revealed in windows for many miles behind the outer margin of the thrust sheet.

At the northeast front of the thrust sheet the rocks above the fault plane are of Carboniferous and early Mesozoic age. To the southwest, near the Idaho-Utah boundary, the plane extends deeper in the section and is overlain by Cambrian rocks. Near the State line the Paleozoic sequence above the fault is exposed in the Bear River Mountains and shows a different facies from that to the east of the Bannock fault in Wyoming. The Middle and Lower Cambrian strata are very thick, and limestones and dolomites of Lower Ordovician and Silurian age appear.

About 100 miles (160 kilometers) west of the Bannock overthrust similar flat thrust sheets are known near Albion, Idaho, on the south edge of the Snake River Plain. Here rocks of Algonkian age are carried eastward over Carboniferous limestones (39, pp. 67–84).

Northeastern Utah.—South of the Idaho-Utah boundary the Bannock overthrust is covered in most places by unconformable Eocene deposits but is traceable along the east side of the Bear River Mountains for 35 miles (56 kilometers) into Utah (44, p. 216). The Paleozoic rocks of the range dip west beneath the synclinorium of Cache Valley but rise to the we t again in the Wasatch Mountains. Here they are underlain by Algonkian quartzites, beneath which, in the vicinity of Ogden, Utah, is the great eastward-tilted Willard overthrust (44, p. 221). Beneath the overthrust are Cambrian shales and sandstones, which rest directly on Archean gneisses. The rocks beneath the Willard overthrust, as exposed near Ogden and to the south in the Wasatch Mountains, are of a different facies from those above it (41, p. 132). They consist of relatively thin Paleozoic formations with many breaks in the sequence and are comparable to rocks of that age in Wyoming. It is now believed that the movement along the Willard overthrust was from west to east and that its eastward dip is a secondary feature. It is not improbable that the Willard is the same fault as the Bannock overthrust, 30 miles (48 kilometers) to the east on the opposite side of the Cache Valley synclinorium (41, p. 133).

The southward continuation of the Willard overthrust in the Wasatch Mountains is not known. About 40 miles (64 kilometers) south of Ogden, in the Cottonwood Canyon and Park City districts, are large eastward-dipping overthrusts in rocks of Cambrian and Mississippian age (44, p. 245). Like the Willard, these have probably moved from west to east. The Cottonwood Canyon and Park City area lies at the junction of the north-south trend of the inner zone of the Cordillera and the east-west trend of the broadly folded Uinta Mountains. In these districts the folds pitch north and south off the westward projection of the Uinta axis, which is also followed by a line of granodiorite intrusions. In the next range west of the Wasatch, the Oquirrh Mountains, the strata also pitch north and south off the western continuation of the Uinta uplift.

Both the north-south and east-west structural lines appear to have had their most active movement toward the end of Cretaceous time, but the right-angled joining of the two suggests that the Uinta axis is an older feature than the folding and overthrusting to the west of it. The arching of the north-south folds and their invasion by granitic masses represent recurrent movements along the Uinta trend (44, p. 251).

GREAT BASIN

The Great Basin is a broad region without exterior drainage which extends from the Wasatch Mountains and Colorado Plateau on the east to the Sierra Nevada on the west. The region is an alternation of desert plains and isolated mountain ranges. Without doubt the ranges have had a complex origin. The outlines of many have probably been determined by relatively recent normal faults which in places transect the structural features within the ranges (64). However, nearly all of them are composed of strongly folded rocks, the differential erosion of which has served to determine the course of their crests and spurs. The trend of many of the ranges bounded by normal faults is roughly parallel to the strike of the folded rocks which they contain, and these trends have been used, in the absence of other information, on the accompanying tectonic map.

Deformation within the Great Basin has taken place during several geologic periods (53, pp. 117–118). In the eastern part of the basin the folding and overthrusting is of late Cretaceous and early Eocene age. In the western half of Nevada the rocks were probably deformed mostly in the late Jurassic, at the time of the orogeny in the Sierra Nevada. In the southwestern part of the basin there has been renewed overthrusting in middle Tertiary time.

Algonkian and Paleozoic stratigraphy.—The eastern Great Basin lies on the site of an extensive and deep Paleozoic geosyncline which escaped conspicuous deformation until Mesozoic or later time. Over the eastern and southern parts of the basin the Paleozoic is underlain with slight unconformity by as much as 10,000 feet (3,050 meters) of little metamorphosed Algonkian strata comparable to the Belt series on the north. In the overlying Paleozoic there is a progressive thickening of the succession westward from the Colorado Plateau (57, pp. 35–37). At Eureka, Nevada, and in the Inyo Mountains of California rocks of this age attain 30,000 feet (9,000 meters) in thickness (59, p. 19). The thin Cambrian succession of the Colorado Plateau increases to the west to as much as 15,000 feet (4,600 meters), partly by the wedging in of the Lower Cambrian at the base (63, p. 555). The Ordovician, Silurian, and Devonian systems are poorly or not at all represented in the plateau, but in parts of the Great Basin, as at Eureka, they consist of 10,000 feet (3,050 meters) of limestone. West of Eureka, in the same manner as in southern Idaho, the Ordovician changes into black graptolite shales (Manhattan district, Nevada, and elsewhere). In the eastern part of the Great Basin there are several thousand feet of Mississippian limestones, which are absent in the western part.

In late Carboniferous time there was a great change in sedimentation. The area of greatest deposition shifted eastward from Nevada to Utah in Pennsylvanian time (67, p. 157). South of Great Salt Lake the series is a mass of quartzite with interbedded limestone 15,000 feet (4,600 meters) in thickness (44, p. 336). Farther west, at Eureka, where the series is 9,000 feet (2,700 meters) thick, the upper third consists of coarse and fine conglomerate. Thin limestones of Permian age are widely distributed over the Great Basin. In western Nevada Permian sandstones directly overlie the Ordovician (54, p. 377). The record of the Carboniferous sediments suggests movements in the region to the west.[9]

Mesozoic stratigraphy.—Triassic and Jurassic rocks similar to those in southeastern Idaho are found along the northeastern margin of the Great Basin. In southern Nevada Triassic and Jurassic continental beds of the Colorado Plateau facies extend westward with the same thickness into the deformed area (63, p. 558; 57, pp. 32–35). Jurassic and Triassic rocks are unknown in the central part of the northern Great Basin, and it is unlikely

[9] Discussed, with a somewhat different interpretation, in 67, pp. 158–161.

that they were ever deposited there. Along its western margin, within the area of late Jurassic movement, they are of a different facies and consist of lavas and tuffs, interbedded with marine shale (62, p. 250), comparable to the strata more extensively developed in the Sierra Nevada to the west. Cretaceous rocks are found only near the eastern margin of the Great Basin, and from their strong clastic and continental development there, it is probable that the region was uplifted, and perhaps even folded, during that period.

Tertiary stratigraphy.—In the eastern part of the Great Basin Eocene sandstones and conglomerates are involved in the block faulting of the region and the later part of the folding, which are the western extensions of the Wasatch formation of the Colorado Plateau. In the northwestern part of the Great Basin basaltic lavas of early Miocene age cover the Paleozoic and Mesozoic rocks along the margin of the Columbia Plateau. In the central and southeastern parts of the basin are younger Miocene continental beds, with fanglomerates at their bases and margins which are transitional into sands, clays, and tuffs (54, p. 377). Locally there is a considerable volume of interbedded lava. The beds were laid down in separated intermontaine depressions, bounded by mountains near the sites of some of the present ranges, but in places they have been raised to mountain heights by later normal faulting. In the southwestern part of the region these beds are sharply upturned and folded and are locally involved in overthrusting.

Older structural features of the Great Basin.—In the eastern part of the Great Basin the trends of the mountains and the folded rocks within them are north or north-northeast, parallel to the margin of the Colorado Plateau. Toward the south, in Utah, the easternmost ranges merge or end southward against the southwestern angle of the Colorado Plateau. In the southwestern part of the basin the north-south chains are replaced by a northwest system parallel to the front of the Sierra Nevada, which flanks them on the west.

Strong folding of the Paleozoic and Mesozoic rocks of the Great Basin has been recognized since the time of the earliest surveys, but in recent years it has been shown that there was also an extensive development of overthrust faults. In some of the districts folding predominated over faulting, but in many places the folds are discontinuous, and the competent sandstones and limestones of the succession have been broken into sheets and thrust over one another without much crumpling. In some places the overriding masses have been split by transverse flaws, which have permitted differential motion between contiguous blocks; in others there have been extensive bedding slips along intercalated incompetent members, allowing the younger rocks of the succession to override the older. Later tilting of the mountains has caused confusing and even reversed dips on some of the thrust planes. These complications of the structure have given them a great irregularity of plan.

Strong deformation and overthrusting from west to east have occurred at many localities along the eastern edge of the Great Basin from southeastern Idaho through Utah to southern Nevada and California. Farther back within the basin there are similar folds and overthrusts. All these features are apparently a part of the same system of deformation.

In the northern part of the Great Basin the mountain ranges consist of broad folds with only subordinate thrust faults. The eastern margin of the belt of deformation lies in the Wasatch Mountains. In the ranges to the west, in the Oquirrh Mountains and the Tintic district (44, pp. 335–402), the Paleozoic limestones and quartzites are thrown into broad, steep folds, but in the Sheeprock Mountains beyond, the limestones are overridden for at least 10 miles (16 kilometers) by a warped mass of Algonkian quartzite (44, p. 432). Farther west, along the western boundary of Utah, there are extensive thrust sheets of older over younger Paleozoic limestones at Gold Hill. In the Ely district, between Gold Hill and Eureka, the limestones are broadly folded but are not thrust-faulted.

In southern Nevada and southeastern California the Great Basin narrows to about half its width to the north by the projection of the southwestern salient of the Colorado Plateau. Here overthrusts predominate over folds. The first range west of the Colorado Plateau (Virgin Mountains) is a tilted block of rocks of the plateau facies. The next range beyond (Muddy Mountains) is capped by a great thrust sheet of geosynclinal Devonian and Carboniferous limestones, resting on Jurassic sandstone and displaced to the east at least 18 miles (29 kilometers) (63, p. 562). The Las Vegas and Spring Mountains, to the west, are built of a group of thrust slices of Paleozoic rocks. Their faults have been traced for a distance of 100 miles (160 kilometers) along the strike, and the displacement on many of them is measurable in miles. The easternmost main thrust carries a sheet of Cambrian limestones eastward and southeastward over a flat eroded surface of faulted rocks as young as the Jurassic (63, p. 564; 57, p. 35). In the Spring Mountains the rocks have been somewhat folded before the thrusting (57, p. 44). Farther south, in the Mohave Desert region of California, strong overthrusting and even conspicuous folding appear to be lacking, though thick Cambrian and other geosynclinal rocks are known.

The thrust structure may terminate to the south against large tear faults.

The overthrusting in the Spring Mountains and Muddy Mountains is older than the Miocene intermontane deposits from which many of the desert valleys of the region are carved (57, pp 54–55). These rocks overlie the eroded surface of the older beds but are themselves broken by large normal faults, which have in part served to outline the mountain areas.

Normal faults in the Great Basin.—Many of the mountain ranges in the Great Basin are broken by normal faults. The outlines of many of the ranges appear to have been determined by fractures of this sort, but there are many contradictory features, caused by the varying ages of the faulting in different parts of the region and by the modification of the faulted topography by subsequent desert erosion.

Some of the normal faults are of considerable antiquity. Many of them have no effect on the topography (63, p. 575). Some of the older and much eroded fault-line scarps are overlapped by Miocene deposits which are not faulted (54, p. 377). Elsewhere the faults are younger, and the Miocene itself is faulted and raised to mountain heights (64, p. 354). For the most part the Miocene beds occupy desert plains between uplifted masses of the older rocks. The surfaces of these lowlands are erosional rather than depositional, and the scarps that face them are fault-line scarps produced by differential erosion. In other places there is abundant evidence that the present relief of the mountains is directly the result of recent faulting (54, p. 378). In such places the downfaulted areas are deeply filled by mountain waste of late Cenozoic age.

Late Tertiary overthrusting in the southwestern Great Basin.—The folding and overthrusting in the eastern and central parts of the Great Basin characterize mountains which have a general north-south trend. In the southwestern part of the basin, along the east flank of the Sierra Nevada, these give place to other ranges which trend southeast. In many of the southeastward-trending ranges there is evidence of post-Miocene folding and overthrusting.

In southern Nevada and adjacent parts of California pre-Cambrian and Paleozoic rocks are thrust for many miles to the east over various strata as young as the Miocene.[11] Farther west, at the south end of Death Valley, the Miocene has been intensely deformed. The southeastward-trending ranges terminate on the south against a great transverse fracture, the Garlock fault. As the ranges approach the fault they are bent

[11] Unpublished paper by D. F. Hewett on the Ivanpah quadrangle.

sharply to the west, as if the mountains on the north side had been moved to the east relative to the area on the south side. The area south of the Garlock fault appears to have been more stable during this deformation, and its rocks are less disturbed.

MEXICAN RANGES

In southern Arizona, southwestern New Mexico, and western Texas the Colorado Plateau is flanked on the south by ranges of folded and faulted rocks like those in the Great Basin. Many of the ranges owe their present outlines to relatively recent normal faults. To the north the folds die out against the Colorado Plateau. Southward the folds continue with increasing prominence into the Sierra Madre of Mexico. The eastern part of the Mexican ranges, or Sierra Madre Oriental, extends progressively eastward south of the Rio Grande. In the State of Vera Cruz it directly faces the Gulf Coastal Plain.

Structure of western Texas and northeastern Mexico.—The mountains of northeastern Mexico, the eastern Sierra Madre, have arisen from a geosyncline which appears to have been a purely Mesozoic feature. The strata of the geosyncline consist of thick deposits of Jurassic and Cretaceous age, with Triassic rocks locally at the base. The rocks of the geosyncline are strongly folded and overthrust toward the east. In eastern Mexico, as far north as Monterrey, they stand in high mountains which rise with steep front along the western edge of the Gulf Coastal Plain. Near Monterrey the Sierra Madre bifurcates northward. The lower outer folds continue northwest and die out near the Rio Grande. The main group of folds bends toward the west for several hundred miles and then continues northward into western Texas.

The change in structure in northern Mexico is related to an early Mesozoic positive area which lay to the south of the Marathon folds of Paleozoic age in Texas. It is probably a remnant of the old hinterland of Llanoria. Over the surface of the positive area Cretaceous rocks directly overlie pre-Cambrian schists or a small thickness of Paleozoic rocks (42, pp. 130–136), whereas in the western branch of the Sierra Madre, west of Monterrey, there is a thick succession of Jurassic as well as Cretaceous strata. The Marathon folds north of the positive area are last exposed to the southwest near the Rio Grande, and their southwestern continuation into Mexico, where they must have been involved in the later deformation of the Sierra Madre, is not known.

The north end of the western branch of the Sierra Madre is exposed in several mountain ranges in the western part of Texas.

Here Jurassic rocks are exposed in the higher folds and are overlain by 5,000 feet (1,500 meters) of Cretaceous sandstones and limestones. The rocks of this district are strongly folded and are overthrust toward the northeast against a thinner sequence of Cretaceous rocks (40, p. 24). They are overlain unconformably by lavas (40, p. 25), probably of Eocene age. The folds of the Sierra Madre continue no farther north than El Paso, Texas, where there are strongly folded Cretaceous rocks in the mountains to the south and block-faulted ridges of Paleozoic rocks in the mountains to the north. The mountains north of El Paso are at the south end of the region of block-faulted rocks in the Rio Grande Valley of New Mexico.

Structure of southern Arizona.—The folded ranges of Sonora and southern Arizona are the northwestern extensions of the folds of northeastern Mexico. In this region the Paleozoic rocks are extensively exposed. The earlier rocks of the group are similar to those of the Colorado Plateau. Cambrian standstones of no great thickness overlie the pre-Cambrian and are succeeded by a few thousand feet of limestones of Cambrian to Mississippian age. These are followed by Pennsylvanian and Permian limestones which thicken southward from the plateau to 5,000 feet (1,500 meters) in southern Arizona. In the western part of Arizona a few remnant areas of Carboniferous limestones rest directly on pre-Cambrian rocks.

The region was broadly folded toward the end of Paleozoic time. Metamorphosed Carboniferous limestones in western Arizona have an east-west strike which diverges from the general trend of the later folds in the region (48, p. 215). In southern Arizona the Cretaceous is unconformable on the Paleozoic rocks and in local areas overlaps across them to rest on the pre-Cambrian.

The Cretaceous of this region consists very largely of clastic rocks. At Bisbee the lower part of the system is 5,000 feet (1,500 meters) thick and consists of fresh-water sandstones and shales with a layer of marine limestone near the middle. Upper Cretaceous sandstones and arkoses are known farther west and north. Near the Gila River coal-bearing and volcanic rocks are present (48, pp. 135–153). The folded Paleozoic and Mesozoic rocks are overlain unconformably by Miocene tuffs and lavas, extensively broken and tilted by normal faults. The intermontane areas are filled by tilted Pliocene fanglomerates and bolson deposits, derived from the erosion of the surrounding ranges.

In southern Arizona the mountains have a general northwest trend, but the folds and faults within the ranges show no such orderly arrangement. At many localities the rocks are traversed by overthrust faults, and it is probable that these have had more than an incidental control of the structural pattern of the region. Along some of the faults pre-Cambrian and Paleozoic rocks have been thrust over the Cretaceous, but along others the upper part of the succession overrides the lower. Most of the overthrusts in the region dip southwest, but a few are tilted northeast, perhaps as a result of later movements. Folds in the sedimentary rocks are discontinuous and appear to result from the irregular deformation of adjacent fault blocks.

The best-known overthrust in the area is the Gold Hill thrust of the Bisbee district, by which Carboniferous limestones are carried for several miles northeast across the Cretaceous (48, p. 286). A short distance to the north, in the Courtland district, are flat thrust sheets of Cambrian rocks overlying Carboniferous limestones. The Santa Rita and Patagonia Mountains, west of Bisbee, are a complex of folded Paleozoic and Mesozoic rocks traversed by a group of overthrusts of northwest trend. North of the Santa Rita Mountains, near Tucson, greatly sheared pre-Cambrian and Paleozoic rocks have been thrust northeast over pre-Cambrian gneisses in the Santa Catalina Mountains (48, p. 227). Pliocene fanglomerates are involved in the movement and are steeply tilted and folded within the deformed area.

North of Tucson the folds and overthrusts disappear toward the Colorado Plateau and the mountains along its southern margin are of blocklike form (48, p. 228). Their rocks are not folded, though they have been extensively broken and tilted by normal faulting.

West and northwest of Tucson the mountains consist of pre-Cambrian schists and gneisses penetrated by younger granites and porphyries and overlain unconformably by Tertiary volcanic rocks. In this part of Arizona high ridges of pre-Cambrian rock, such as the Bradshaw Mountains, flank the Colorado Plateau on the southwest (48, p. 211). They were apparently covered by only a small part of the sedimentary succession exposed to the east of them, and they may have stood as a positive area between the deformed rocks of southern Arizona and those of the Great Basin.

SIERRA NEVADA PROVINCE

Geographic limits.—The region of Sierra Nevada structure extends along the western edge of the Cordilleran system. Its most prominent structural features were produced before those of the mountains to the east, in late Jurassic time, with the eastern limit of the deformation extending somewhat to the east of the present mountain area. The province is separated from the Pacific coast by a belt of younger mountains, the Coast Ranges.

Topographically the most prominent part of the province is the Sierra Nevada of California, which has attained its present height as a result of late Cenozoic faulting and tilting (61, p. 9). To the south the province extends into the mountains of Lower California and to the north into the Klamath Mountains of northern California. The folds in the Klamath Mountains pass to the northeast beneath the lavas of the Columbia Plateau but reappear in the Blue Mountains of northeastern Oregon (51, p. 12). Farther north the ranges of central Idaho and the Purcell, Selkirk, and Cascade Mountains on the Canadian border show structural features of the same age and character.

General features.—The Sierra Nevada province is characterized by granite batholiths of vast extent, which have invaded and metamorphosed a succession of Paleozoic and early Mesozoic rocks. In some places the plutonic rocks occupy nearly the whole of the exposed mountain areas. The Sierra Nevada batholith covers an area of 20,000 square miles (51,800 square kilometers), and farther north the Idaho batholith occupies an area of equal size. Both east and west of the principal masses stocks of plutonic rock intrude the inclosing sediments.

The sedimentary rocks of the Sierra Nevada province record an eventful tectonic and volcanic history prior to the climax of the movements in middle Mesozoic time. They are of a characteristic facies. Limestone beds are rare and lenticular; the greater part of the succession consists of sandy and slaty rocks with numerous flows and tuffs. Deformation is recorded during various Paleozoic and early Mesozoic epochs, but the most pronounced deformation in California appears to have occurred during the late Paleozoic (60, p. 9). Along the western edge of the Sierra Nevada province Cretaceous sandstones and shales overlap the eroded edges of the older folds and are not greatly deformed or metamorphosed.

Lower California.—The southernmost member of the Sierra Nevada system is the province of Lower California, which extends southward from Los Angeles into the peninsula of Baja California in Mexico. The province contains a great central mass of granodiorite with a few roof pendants and marginal areas of Paleozoic or early Mesozoic slates (69, p. 358). In southern California the rocks intruded by the granodiorite are known to be of Carboniferous and Triassic age. The granodiorites and the rocks invaded by them are overlain unconformably by Cretaceous and Tertiary strata. The mountain ridges of the area have been raised by late Cenozoic faults, which bound the east side of the province. They rise with bold scarps above the Imperial Valley of southern California, and farther south they flank the west side of the Gulf of California.

The northern extension of the mountains of Lower California is separated from the Sierra Nevada on the north by an area of complex faulting, covered for the most part by rocks of Tertiary age.

Sierra Nevada.—The Sierra Nevada extends north-northwest for a distance of 400 miles (640 kilometers) from south-central to northern California. It is bounded on the east by the Great Basin and on the west by the Great Valley of California, which separates it from the Coast Ranges.

Sedimentary rocks of Carboniferous and early Mesozoic age are exposed in the northern part of the Sierra Nevada. The Carboniferous rocks (Calaveras formation) are predominantly black slate but include prominent quartzitic and volcanic members and some lenses of limestone. The greater part of the Calaveras is probably of Mississippian age, but older and younger strata may be present. To the north Pennsylvanian sandstones and tuffs come in above the Calaveras. The Paleozoic rocks of the Sierra were strongly folded and metamorphosed before Mesozoic time and were intruded by diorites (60, p. 9). For the most part, these earlier features are obscured by those of later date, but in places the Jurassic is seen to overlap the Paleozoic rocks with marked difference in dip.

In the main part of the Sierra the Calaveras is overlain by slates, graywackes, and tuffs of Jurassic age; (Mariposa slate; 60, p. 9). Triassic slates and volcanic rocks intervene to the north and east and are also found in the western part of the Great Basin.

The sedimentary rocks of the Sierra Nevada are invaded by basic igneous rocks now altered to amphibolites and serpentines and by great batholithic masses of granite and granodiorite (62, pp. 254–255). These occupy most of the mountain area in the southern two-thirds of the range. To the north the large batholithic masses lie in the eastern part of the mountains, and to the west the plutonic rocks occupy smaller lenslike or subcircular areas inclosed by sedimentary rocks. For the most part, the batholiths of the Sierra are concordant with the sedimentary beds that inclose them (46, pl. 2) and appear to have forced them apart during their intrusion.

The sedimentary rocks of the northern Sierra Nevada dip to the east at high angles and strike north-northwest, parallel to the trend of the present range. For part of their length they are traversed by the Mother Lode, a complex fault zone, intruded by lenslike masses of serpentine and amphibolite (60, pl. 2). Rocks of the Calaveras formation have been thrust southwestward against the Mariposa slate along the Mother Lode fault zone.

East of the Sierra, in the western Great Basin, are Triassic and Jurassic rocks similar to those in the mountains. These are invaded by small batholithic masses of granitic rock. The rocks are less intensely deformed than in the mountains to the west.

The deformed rocks of the Sierra are overlain on the crests of the mountains by residual patches of Miocene stream gravel and flows of andesitic lava (61). These deposits were laid down on an eroded surface of moderate relief, which has since been tilted to the west during the profound normal faulting along the eastern border of the mountains (69, pp. 351–352). There is also a possibility that, in its southern part, the rocks of the Sierra Nevada have been thrust toward the east, against those of the Great Basin.

Klamath Mountains.—The Klamath Mountains of northern California and southwestern Oregon lie on the northwestern extension of the Sierra Nevada. The mountains cut across the north end of the Valley of California and the Coast Ranges, so that they directly face the Pacific Ocean near the California-Oregon boundary. Farther north, in Oregon, Coast Ranges like those in California appear.

The rocks of the Klamath Mountains are not as greatly metamorphosed as those in the Sierra Nevada and are intruded by fewer plutonic masses, so that their sedimentary succession is much plainer. Here, as in the Sierra, the section consists of clastic and volcanic Paleozoic and early Mesozoic rocks. A basement of ancient schists is revealed in the central and western part of the mountains (51, p. 14), overlain by 10,000 to 15,000 feet (3,050 to 4,600 meters) of Silurian, Devonian, Mississippian, and Permian rocks. Strata of Pennsylvanian age are apparently absent from most of the area. Most of the succession consists of black slates, sandstones, and tuffaceous rocks (51, pp. 14–15), but there are some layers of fossiliferous limestone.

These strata are overlain, locally with considerable unconformity, by 5,000 to 10,000 feet (1,500 to 3,050 meters) of Triassic and Jurassic clastic and tuffaceous rocks. In southwestern Oregon the Jurassic contains radiolarian cherts and glaucophane schists. In places the two systems are separated by an unconformity. All the rocks of the Klamath Mountains as high as the Jurassic are strongly folded and are invaded by large masses of serpentine and greenstone. On the southwest and northeast their eroded surface is overlain by tilted Cretaceous and Eocene sandstones (51, p. 18).

The pre-Cretaceous folds in the Klamath Mountains have an arcuate plan. In the south their structure continues the north-northwest trend of the Sierra Nevada, but near the Oregon boundary they turn to the north-northeast or northeast. The structure of the mountains is obscured by long, narrow belts of basic intrusives which have been injected along the strike of the rocks (52, p. 4). The rocks of the Klamath Mountains dip to the east at high angles (51, p. 22). In their western part, not far from the California-Oregon boundary, the mountains are traversed by several large overthrust faults, which dip to the east (69, p. 350).

At their northeast end the folds of the Klamath Mountains pitch beneath Miocene basalts of the Columbia Plateau.

Blue Mountains.—In the Blue Mountains of northeastern Oregon, on the extension of the trend of the Klamath Mountains, rocks of similar character and structure reappear from beneath the Columbia River lava. The sedimentary succession begins with Mississippian limestones and cherts, overlain by younger Carboniferous volcanic rocks. These are separated by a marked structural break from Triassic and Jurassic clastic rocks (68, p. 223). There is also a considerable unconformity between these two systems, probably accompanied by the injection of plutonic rocks. The Jurassic is itself invaded by large masses of granite and granodiorite, and the whole succession is strongly folded (68, p. 223). Along their margins the mountains are overlapped by tilted Cretaceous sandstones and sheets of Tertiary basalt.

The strike of the folds in the Blue Mountains is east and west, but the Tertiary folds cross them in a northwesterly direction and outline the form of the present mountain areas.

Structural features of Sierra Nevada type in the northwestern United States.—At the east end of the Blue Mountains, near the Oregon-Idaho boundary, the folds in the Paleozoic and early Mesozoic rocks turn once more toward the north. The rocks are invaded toward the east by the Idaho batholith, which occupies most of the central portion of that State and covers an area of about 20,000 square miles (51,800 square kilometers). This mass of granodiorite spreads irregularly eastward through the inner folds of the northern Rocky Mountains, with many offshooting tongues and outlying masses. To the northeast it invades rocks of the Belt series (Algonkian), and to the southeast it invades Paleozoic geosynclinal strata. The batholith is overlain unconformably by Tertiary lavas.

Farther northwest, in northern Washington, extensive mountainous areas with structure like that in the Sierra Nevada rise from beneath the Miocene lavas at the north edge of the Columbia Plateau. These ranges include the Purcell, Selkirk, and northern Cascade Mountains. Here there are Carboniferous and Triassic rocks of great thickness, in places strongly metamorphosed and invaded by great batholiths of granodiorite. Near the Canadian boundary, in the northern Cascade Range, these rocks are overlain unconformably by small areas of Cretaceous clastic rocks, which reach 30,000 feet (9,000 meters) in thickness (47, pp. 547–565). Farther south in the Cascade Range the

Cretaceous is absent and the metamorphic rocks are overlain by gently folded Eocene clastic and volcanic rocks, which are in turn covered by Miocene lavas. In this region there is a large granodiorite batholith of Miocene age (69, pp. 347–348).

Columbia Plateau.—A wide area in the northern part of the Sierra Nevada province is covered by a vast flood of basaltic lava (62, pp. 265–267). This is the Columbia Plateau of Oregon and southern Washington.

The chief eruptions in the region occurred in Miocene time and were predominantly of basaltic composition. Along the margins of the plateau, where the underlying rocks are exposed, andesitic and rhyolitic lavas of Eocene age are found. The lavas were poured out on an area of considerable relief, so that areas of the older rocks, such as the Blue Mountains, project above them like islands (69, p. 339). Since their formation the lavas have been broadly flexed and folded.

Along the western margin of the plateau a chain of volcanoes of andesitic lava have been built up to form the Cascade Mountains. Volcanic activity in the region has persisted from Miocene to relatively recent time.

East of the Columbia Plateau, in southern Idaho, is the Snake River Plain, which occupies a downwarped area in the older rocks extending irregularly east and west across the Cordilleran trend (39, p. 85). The plain is covered by basaltic lavas, for the most part younger than those in the Columbia Plateau, and here also volcanic activity has persisted to relatively recent time.

COAST RANGES

GENERAL FEATURES

The Coast Ranges, raised in Cenozoic time and composed for the most part of Tertiary rocks, extend along the Pacific coast of the United States in a belt of mountains 100 miles (160 kilometers) in width. Near the California-Oregon boundary they are interrupted by the older rocks of the Klamath Mountains, which for a short distance face directly on the Pacific coast. South of this, in middle California, the ranges are bounded on the east by the Valley of California, which separates them from the Sierra Nevada. At their south end, in southern California, the Coast Ranges give place to the mountains of the province of Lower California. Through most of their extent the topographic and structural features of the Coast Ranges trend roughly parallel to the Pacific coast. In southern California, however, in the vicinity of Los Angeles, most of the structural features strike nearly east and west, transverse to the general trend.

The northern Coast Ranges are heavily wooded and are poorly known geologically. South of San Francisco the country is more open, and much impetus has been given to geologic study by the search for oil. This part of the province will be more fully discussed here.

Structure.—The rocks of the Coast Ranges of California are considerably folded and are traversed by numerous steeply dipping faults of greater or less magnitude. The structural features have resulted from compressive forces, but there are relatively few overthrusts of any size, of the sort which characterize mountains of the same age in other parts of the world. Movements on the structural lines have been recurrent. There have been disturbances at least as far back as the Cretaceous and early Tertiary, and some as late as historic time.

Stratigraphy.—The oldest rocks in the Coast Ranges are schists and marbles, which are intruded by granodiorite. The next youngest strata, of probable Jurassic age (Franciscan), are found only in fault contact with the metamorphic and plutonic rocks (79, p. 7). The Franciscan is a thick mass of sandstones and graywackes with beds of radiolarian chert and local areas of glaucophane schist. The probable Jurassic and older rocks form the basement of the Coast Ranges.

Unconformably overlying the Franciscan are thousands of feet of Cretaceous and Tertiary strata. Most of these are of clastic character and consist of sandstones and shales, with local conglomerate beds. There are few limestone layers, but some parts of the section, notably in the Miocene, include fine-grained, diatomaceous siliceous sediments. The thickness and lithologic character of the strata change along the strike, in places with great rapidity.

Unconformities are found at many places in the section, but most of them are of local extent and are determined by uplifts and subsidences in relatively small areas. There appear to have been two periods of widespread movement. In one of these, recorded by marked discordances at the base or middle of the Miocene, the crystalline rocks were faulted and the sedimentary rocks folded, producing radical changes in conditions of erosion and sedimentation. In the other, which occurred in middle Pleistocene time, folding, faulting, and in places overthrusting occurred, and the mountains of the region received their present forms and outlines.

COAST RANGES OF OREGON

The rocks of the Coast Ranges in Oregon are largely marine sediments of Tertiary age, with basaltic and other intrusives and with intercalated flows and pyroclastic rocks. The Coast

Ranges form an anticlinorium, with the steepest folds on the west side and with the Willamette Valley cut into the soft Oligocene tuffs on the eastern slopes. These tuffs dip east under the Cascade Range and are a part of a block or series of blocks that were elevated along their western edges during Pliocene time, with perhaps a fault along the coast.

The folds of the Coast Ranges of Oregon are interrupted by the Klamath Mountains on the south. They are separated from the Coast Ranges of California by the older rocks of these mountains, which for some distance near the California-Oregon boundary face directly on the Pacific coast.

COAST RANGES OF CALIFORNIA

Valley of California.—The Valley of California is a great longitudinal depression, 400 miles (640 kilometers) in length and 50 miles (80 kilometers) in width, separating the Coast Ranges from the Sierra Nevada. It is also a structural depression.

Along the eastern margin of the valley Cretaceous and Tertiary strata overlap the old rocks of the Sierra Nevada and dip gently westward at the same inclination as the surface of the Sierra block (75, pp. 230–231). The valley is thickly filled by rocks of these periods, which apparently are not greatly folded. They are overlain by a thick cover of Pleistocene deposits.

The western margin of the valley is a complex zone of folding and faulting. The rocks of the Coast Ranges to the west have in part been greatly uplifted, so that the basement rocks are exposed in places close to the margin of the valley. Along the western margin the Tertiary rocks have been folded into sharp anticlines, which diverge southeastward from the front of the Coast Ranges, pitching and flattening toward the valley (74). Many of these form reservoirs for oil.

San Andreas fault.—One of the major structural features of the Coast Ranges in California is the San Andreas fault,[12] which has been traced from the Imperial Valley to Punta Arenas, north of San Francisco, a distance of 600 miles (960 kilometers) (80). It extends diagonally across the Coast Ranges. At its south end it lies considerably to the east of them, farther north it flanks their east side, near San Francisco it lies within the ranges, and to the north it passes beneath the waters of the Pacific Ocean.

The fault trace is marked by a curiously straight and almost continuous chain of ridges, scarps, and depressions, most of which involve Quaternary alluvium. In some places the fault lies at the edge of mountain ranges, in others it crosses the ranges, and

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[12] Most of the information in this section is derived from notes furnished by L. F. Noble.

in still others it extends across lowlands far from any mountain area. Bordering the fault is a belt of roughly parallel, branching, and interlacing fractures that in places attains a width of several miles. The fractures cut the country rock into a mosaic of wedges elongated parallel to the main fault, so that the dominant structure is a sort of slicing.

Movements on the San Andreas fault have been both horizontal and vertical. The vertical movements differed in direction at different places along the fault. In 1906 there was movement along the northern 187 miles of the fault trace at the time of the San Francisco earthquake, and the west side was offset as much as 21 feet (6.4 meters) to the north, relative to the east side. East of Los Angeles an apparent offset of topographic and geologic features suggests an earlier and greater movement in the same direction.

The San Andreas fault is interpreted as the result of compressive forces along a great shear zone. The fault is an old line of weakness on which movements have been recurrent in Quaternary and Tertiary time and perhaps in pre-Tertiary time.

Coast Ranges of middle California.—The Coast Ranges of middle California are about 70 miles (113 kilometers) in width and form a rugged mountainous area which rises steeply from the Valley of California on the east and the Pacific Ocean on the west. The mountain ridges are separated by narrow longitudinal valleys, many of which follow fault lines.

The Cretaceous and Tertiary rocks of the region reach a thickness of more than 25,000 feet (7,600 meters) (79, pp. 7–15). The Lower Cretaceous rocks, composed of fine clastic deposits, rest without great discordance on the Franciscan (79, p. 19), and it was not until Upper Cretaceous time that coarse clastic sediments were laid down. Locally the Cretaceous is separated from the earliest Tertiary by a pronounced unconformity, but the greatest break in the sequence is near the base of the Miocene. As a result of the middle Tertiary movements, the Miocene and in places the Pliocene strata overlap all the older formations down to the pre-Franciscan in the higher positive areas. In near-by negative areas great thicknesses of Tertiary strata are found in nearly unbroken sequence. The Pliocene was laid down in smaller basins than the older strata in middle California, and the Pleistocene is only meagerly represented.

The Coast Ranges of middle California are crossed obliquely by the San Andreas fault. Other faults, thrusts, and folds have a similar oblique trend across the ranges and terminate northwestward on the coast and southeastward at the margin of the Valley of California. At San Francisco (79, fig. 3) and probably in other parts of the Coast Ranges to the south (76, pp. 770–772) the region is divided by the larger faults into blocks 5 to 15 miles (8 to 24 kilometers) in width. These blocks appear to have been persistent positive or negative areas during Tertiary time, and each has had a distinct depositional history.

In a few places the rocks are broken by overthrust faults. One of these, near Mount Diablo, east of San Francisco, has carried Franciscan and Tertiary rocks for several miles westward over the Cretaceous (76, p. 776).

Southern Coast Ranges.—Not far north of Los Angeles the northwest system of folds and faults of the middle Coast Ranges is replaced by others of east-west trend. Toward the west the east-west mountainous areas partly surround basins of thick sedimentation which fringe the Pacific coast. Toward the east they block off the south end of the Valley of California and connect the Coast Ranges with the Sierra Nevada.

In the southern Coast Ranges coarse clastic rocks of Upper Cretaceous age rest directly on the basement rocks and were derived from the erosion of uplifted granitic areas. The Tertiary, up to the lower Miocene, consists of fine clastic deposits. These are overlain by coarse conglomerates of middle Miocene age, with local boulder beds and volcanic rocks, which pass upward into diatomaceous siliceous shales. Locally, as in the Santa Monica Mountains, the middle Miocene beds rest on the older rocks with marked discordance. The succeeding Pliocene and lower Pleistocene rocks are clastic and reach 20,000 feet (6,100 meters) in thickness in the deeper basins. These and the underlying rocks are strongly deformed and are overlain by a smaller thickness of nearly undisturbed later Pleistocene rocks.

The Ventura Basin, northwest of Los Angeles, lies between the eastward-trending Santa Ynez and Santa Monica Mountains. The Tertiary rocks of the basin reach 40,000 feet (12,000 meters) in thickness, and over half of them are of Pliocene age (78, pp. 8–9). The region consists of parallel belts of mountains and lowlands that were produced by the middle Pleistocene deformation. The lowlands are synclinal areas which are still receiving deposits. The mountains on the north side of the basin and within it are either uplifted fault blocks or upraised masses of closely folded rocks, overturned and overthrust to the south (78, pls. 2 and 7). The Ventura Basin is separated from the Los Angeles Basin, to the southwest, by the Santa Monica Mountains, a broad arch uplifted in both middle Miocene and middle Pleistocene time, on whose crest basement rocks are exposed (77).

The Los Angeles Basin [13] is a broad syncline bordered on the north, east, and to a certain extent on the southwest by elevated,

[13] From descriptions by H. W. Hoots and H. S. Gale in the Southern California guidebook of this series.

intricately folded and faulted hills and mountains. The bordering highlands were raised by middle Pleistocene movements, and on them remnants of the uplifted predeformation topography are still preserved. On the flanks of some of the highlands a dozen or more successive terraces may be seen. The highlands on the north are separated from the Los Angeles Basin by steeply dipping faults of large displacement. The Los Angeles Basin contains as much as 10,000 feet (3,000 meters) of marine Pliocene and Pleistocene strata. It is crossed in a northwesterly direction by lines of anticlinal folding. These anticlines are likewise of middle Pleistocene age, and most of them rise in low hills. Some of the anticlines yield oil.

Northeast of Los Angeles are the Tehachapi and other ranges, which form a complex knot of faulted mountains joining the Coast Ranges with the Sierra Nevada. They are masses of granitic and metamorphic rocks that stood as a barrier between the area of Tertiary marine deposition of the Valley of California and that of continental deposition in the Mohave Desert (75, pp. 205–208). Several of the mountains of the region are slabs of granite thrust over Tertiary strata along low-angle faults.[14] The Tehachapi Mountains are bounded on the southwest by the San Andreas fault.

Southeast of these ranges, and separated from them by a broad westward reentrant of the Mohave Desert, are the San Gabriel and San Bernardino Mountains (81). These are composed of basement rocks. They are separated at Cajon Pass by the San Andreas rift, which appears to have offset the San Gabriel mass to the northwest relative to the San Bernardino mass, although the offset has not been proved.

Relation of the Coast Ranges to the Lower California province.—South of Los Angeles the folded and faulted sedimentary rocks that characterize the Coast Ranges farther north are restricted to a narrow belt along the coast. Inland are mountains composed of plutonic and metamorphic rocks, whose structural features are of Sierra Nevada type. On these older rocks are superimposed a fault system like that in the Coast Ranges farther north.

[14] Personal communication from L. F. Noble. See also Buwalda, J. P., Gazin, C. L., and Sutherland, J. C., Frazier Mountain, a crystalline overthrust slab west of Tejon Pass, southern California [abstract]: Geol. Soc. America Bull., vol. 41, pp. 146–147, 1930.

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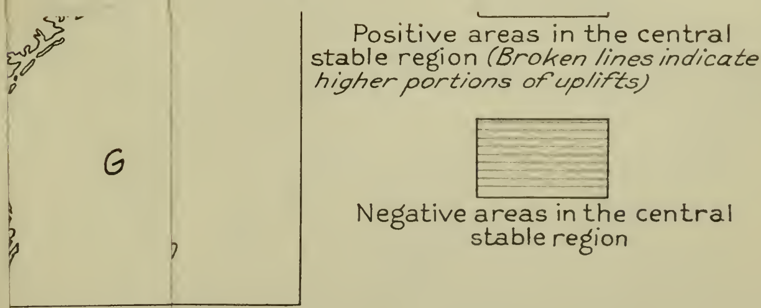

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MAP OF THE UNITED STATES SHOWING PRINCIPAL STRUCTURAL FEATURES

100 0 500 MILES

100 0 500 KILOMETERS