The geologic history of New Mexico is wonderfully diverse. Exposed within the state's boundaries are Precambrian igneous and metamorphic rocks more than 1.5 billion years (b.y.) old, sedimentary strata representing each geologic period from Cambrian to Quaternary, and a variety of volcanic rocks erupted over the past 60 million years (m.y.) to within a few hundred years of the present. Study of these rocks and their relationships within the structural, tectonic, and geomorphic framework of New Mexico's present landscapes has yielded much information on the geologic evolution of the state. Because of the complexities of New Mexico's geology, however, only a brief outline of especially important aspects of the state's geology can be presented here. Some additional details of New Mexico stratigraphy and structure may be found in the discussion of the state's paleontology and young faulting elsewhere.

New Mexico's Precambrian rocks are exposed predominantly in the cores of mountain ranges along the east side of the Rio Grande and in a few isolated ranges to the west, such as the Brazos, Nacimiento, Zuni, and Barros mountains. A wide variety of metamorphic and igneous rock types is present, with much local variation and many complex structures. In general the pattern seems to have been initial deposition and gradual burial of clastic sediments about 2 b.y. ago (probably at the edge of an ancient continent), accompanied by several episodes of extrusive volcanic activity, and followed by extensive regional folding, faulting, and metamorphism. Deformation and metamorphism wrought dramatic changes in the volcanic and sedimentary rocks: clastic sediments became contorted phyllites, schists, and quartzites, and the extrusive volcanics were transformed into sheared belts of felsites and amphibolites. Intrusion of granitic magmas overlapped the long continuing tectonism and metamorphism, producing metamorphosed gneisses, in addition to large volumes of undeformed granite. Pegmatite dikes, representing final crystallization of magmas and containing beryl, lepidolite, tantalite, and other rare minerals, were injected locally into older granites, most notably at the Harding pegmatite mine near Dixon, and in the Petaca District of the Brazos Mountains.

These events appear to have begun earlier in northern New Mexico. Precambrian rocks in the Brazos, Taos, and Nacimiento mountains have been dated at 1.7 to 1.8 b.y., whereas the Precambrian cores of the Zuni, Manzano, Ladron, and Magdalena mountains are 1.3 to 1.6 b.y. old, and the Sandia Granite is about 1.45 b.y. old. Farther south, in the San Andres Mountains, Precambrian ages are 1.3 to 1.4 b.y., and the Precambrian of the Franklin Mountains near El Paso is scarcely 1 b.y. old. As Precambrian metamorphic and igneous activity subsided, the landscapes began to be eroded, and, with the waxing and waning of Paleozoic seas across New Mexico, were in most areas eventually covered by Paleozoic sediments. Uplift during late Tertiary time, associated primarily with tectonic movement along the Rio Grande rift, has once again exposed some of these Precambrian rocks.

Through the Paleozoic Era most of the state was covered by vast shallow seas in which thick sequences of limestones, sandstones, and shales accumulated. The sedimentary record for the Cambrian through Devonian periods is limited to the mountain ranges in the south-central and southwestern part of New Mexico; erosion of early and middle Paleozoic sediments in northern New Mexico occurred later in the Paleozoic. Through the Mississippian and Pennsylvanian periods, marine sediments were deposited in many parts of New Mexico. Renewed uplift in the Pennsylvanian created several large north-south trending islands that divided the northern seas, and by the beginning of the Permian these islands had coalesced into a landmass that shed great volumes of red clastic sediments, pushing the shoreline inexorably southward. These events corresponded temporally to the worldwide assembly of supercontinent Pangaea. In southern New Mexico the tropical seas in which the great Capitan Reef Complex grew persisted until nearly the end of the Permian, but eventually dwindled and vanished, leaving thick sequences of salt and potash over much of southeastern New Mexico.

Rocks of Triassic and Jurassic age are confined mainly to the northern half of the state and were deposited as rivers spread eroded sediments across vast continen-
tal plains toward oceans to the west. Colorful red, green, gray, brown, and white sandstones and shales of the Chinle and Morrison formations represent these periods in many parts of northern New Mexico.

By the last half of the Cretaceous period the seas had returned; New Mexico was on the western shoreline of a great shallow ocean that covered most of central North America. Numerous advances and retreats of the shoreline produced a great variety of marine and swampy facies. The classic sequence in the San Juan Basin is the best and most easily observed example, for these Cretaceous units are widely exposed today over much of the northwestern quarter of the state. Most of New Mexico’s coal deposits formed from the lush vegetation that existed in northwestern and northeastern New Mexico during this time. The sea retreated quickly out of the state at the close of the Cretaceous, the last time New Mexico would be covered by marine waters. About the same time, the Laramide orogeny, a profound mountainbuilding episode centered to the west of the state, intensified volcanic activity and uplift in the San Juan Mountains of southwestern Colorado and neighboring areas. Large volumes of clastic sediments were deposited by rivers across much of New Mexico, concentrating in structural depressions such as the San Juan and Raton basins. Local and sporadic volcanic and igneous activity also characterized some parts of New Mexico during the early Tertiary; the internal parts of these volcanic systems are now exposed as stocks and dikes mainly in southwestern New Mexico.

Beginning about 40 m.y. ago, much of southwestern and central New Mexico was subjected to an enormous explosion of volcanic activity that lasted about 20 m.y. before subsiding. Great thicknesses of ash-flow tuffs, along with andesite, rhyolite, and basalt flows, originated from gigantic volcanic cauldrons (some more than 50 km in diameter) as a consequence of complex interactions between two colliding lithospheric plates along the western coast of North America. Many of the cauldrons are not obvious in the present landscape, having been obscured by subsequent geologic events, but they form the cores of some of the most conspicuous topographic features of southwestern New Mexico, such as the Mogollon-Datil plateau, Black Range, and Organ, Magdalena, San Mateo, and Peloncillo mountains. Hydrothermal fluids associated with this volcanism produced some of New Mexico’s most important metallic resources. Other large volcanic masses in central New Mexico (e.g., Sierra Blanca and the Capitan and Ortiz mountains) formed about this time, which also witnessed the final uplift of the Sangre de Cristo Mountains. Locally, the eroded necks of isolated volcanos which formed in the middle Tertiary, such as Shiprock, still project above the modern landscape.

Continued crustal instability, chiefly extension, was also responsible for initiating, about 30 m.y. ago, the Rio Grande rift, a great north-trending structural depression that bisects the state. Along the eastern edge of the rift, fault blocks have been uplifted gradually to form a line of prominent mountain ranges, and the basins within the rift have accumulated thousands of meters of Miocene to Recent sediments. Continued evolution of the rift has also assured a strong igneous imprint on the geologic history of western and central New Mexico. In the Jemez Mountains, volcanism began about 10 m.y. ago, producing a series of basaltic and rhyolitic flows. As the magma chamber underlying the area became depleted, explosive eruptions beginning about 1.4 m.y. ago spread ash-flow tuffs and pumice across the Bandelier area, and scattered ash as far east as Kansas. Collapse subsequent to these eruptions created the Valles Caldera, with a diameter of 22 km, one of the largest in the world. After caldera collapse, magma continued to be extruded until a few tens of thousands of years ago. Extensive volcanism also began in north-central New Mexico about 8 m.y. ago and left more than 100 cones as well as widespread lava flows covering more than a quarter of Union and Colfax counties. Volcanic activity continued here until about 4,500 years ago, and some of the youngest volcanos, such as Capulin, are virtually intact.

In west-central New Mexico the Mt. Taylor volcanic field flourished from about 3.5 to 2 m.y. ago; Mt. Taylor itself was built up over more than a million years of intermittent activity. The larger Zuni Bandera field southwest of Grants is an enormous area of malpais and volcanic cones that originated about 1.5 m.y. ago, and lava extrusion has continued nearly to the present. The McCarty’s flow is one of the most voluminous volcanic flows in the world that has occurred in historical times; its eruption about A.D. 1300 has been recorded in Indian stories. The extensive malpais near Carrizozo is not much older (perhaps 1,000-1,500 years old). Within about the past million years significant volcanic activity has also occurred southwest of Las Cruces and in several places along the west side of the Rio Grande in the Albuquerque area. The Albuquerque volcanos and related structures are between 150 and 200 thousand years old.

During the late Tertiary and Quaternary periods, sediments continued to be deposited in all parts of the state. The surface of the High Plains of eastern New Mexico is of this age, and thick Pleistocene sedimentary de-
Deposits have built up along the Rio Grande and many other rivers within the state. Erosion and deposition proceed rapidly compared to most other geologic processes, and many of the most conspicuous features of the present landscape—from the familiar desert mesas and buttes to the intricately dissected badlands of northwest and central New Mexico to the windblown gypsum dunes of White Sands—are all the result of very recent geologic processes.

A physiographic province is a region with a particular pattern of landforms that differs significantly from that of adjacent regions. Each province has a distinctive geologic framework and particular combinations of topographic and hydrographic features that have evolved through geologic time. The individual landforms (e.g., mountains, canyons, alluvial fans) that in aggregate make up the varied natural landscapes of a given province reflect a variety of geomorphic processes. In New Mexico these range from the action of deep-seated (hypogene) forces, including volcanism and tectonism, to surficial (epigene) processes, such as erosion and sedimentation by water or wind.

The Southern Rocky Mountain Province extends from Colorado into the north-central part of the state as a two prong system of high ranges separated by deep structural basins of the northern Rio Grande rift. The eastern prong of the Southern Rockies includes several ranges of the Sangre de Cristo Mountains between the San Luis and Española rift basins and the Raton Section of the Great Plains. The area east of Taos also includes the high, parklike Moreno Valley between the central Sangre de Cristos and the Cimarron Mountains. The western mountain prong between the Navajo Section of the Colorado Plateau and the Rio Grande rift basin includes the Brazos uplift to the north and the outlying San Pedro, Nacimiento, and Jemez mountains to the south. The latter highland areas, located south of the lower Chama Valley, are transitional to the southwestern Colorado Plateau and Basin and Range provinces.

The Sangre de Cristo, Brazos, and San Pedro-Nacimiento ranges have cores of Precambrian crystalline rocks overlain by Paleozoic, Mesozoic, and lower Cenozoic sedimentary rocks. Cenozoic volcanic and sedimentary rocks cap the ranges in a number of areas. Numerous glaciated peaks and alpine valleys are present in the Sangre de Cristos north of Santa Fe and in the Brazos uplift near the Colorado border. Among these peaks is Wheeler Peak (13,161 ft), the high point of the state, northeast of Taos. Valleys draining areas of alpine glaciation (e.g., Chama, Costilla, Red, Embudo-Santa Barbara, Nambe, Santa Fe, Pecos, Mora) have stepped sequences of glacial-outwash terraces.

The Jemez Mountains west of Los Alamos (maximum elevation 11,561 ft.) are primarily a constructional feature built by late Cenozoic volcanism. Eruptions of Pleistocene age produced the huge Toledo-Valles caldera complex as well as the Bandelier Tuff that caps the Pajarito Plateau at the western edge of the Española structural basin.

The Southern Rocky Mountain Province also includes the San Luis Valley, a Rio Grande rift basin that is transitional southward to the Española Valley in the Basin and Range Province. At the southern end of the basin, the Rio Grande has cut a deep gorge (canyon walls up to 1,000 ft. high) in the thick accumulation of Pliocene basalt flows that forms the central Taos Plateau. The eastern part of the plateau includes a constructional plain built by alluvial fans at the base of the Sangre de Cristos.

The Colorado Plateau Province in northwestern New Mexico is part of a larger region (extending into Arizona, Utah, and Colorado) characterized by erosional landscapes carved on relatively undeformed sequences of sedimentary and volcanic rocks. The Zuni Mountains between Gallup and Grants are the only major mountain uplift. The summit of the Mount Taylor volcanic center (elevation 11,301 ft) is the highest point in the New Mexico part of the province. Major landforms include scarp-bounded tablelands (plateaus, mesas, buttes, and benches), cuestas, hogbacks, and a variety of valley and canyon types. The province straddles the continental divide (6,675 to 9,916 ft elevation range) and contains headwaters of the Rio Chama and Rio Puerco (Rio Grande system) on the east, and the San Juan and Little Colorado rivers on the west.

The Navajo Section of the Colorado Plateau is dominated by two structural basins with thick sequences of gently dipping Mesozoic and lower Cenozoic sedimentary rocks, mainly shale, mudstone, and sandstone with extensive coal seams. The large San Juan Basin lies between the Southern Rockies, the Four Corners platform, and the Zuni-Defiance uplift. The smaller Gallup-Zuni basin is located south and west of the Zuni Mountains. The Chuska Mountains (maximum elevation 9,370 ft), along the New Mexico - Arizona border, are a tableland with prominent bounding escarpments. Prominent volcanic necks, such as Shiprock, in the Four
Corners area north of the Chuskas result from exhumation of feeder conduits at middle Cenozoic volcanic centers.

Aside from narrow hogback belts eroded on steeply dipping strata of monoclines flanking major structural upwarps, the Navajo Section is characterized by broad rolling plains carved on easily eroded rocks, and cuestas and tablelands capped by gently dipping resistant sandstone beds. Canyonlands and escarpments of moderate local relief occur mainly in the eastern part of the San Juan Basin. However, most stream valleys are broad with relatively short canyon reaches; areas of high cliffs and escarpments are of limited extent.

The highest point in the New Mexico part of the Navajo Section is at Chromo Mountain (elevation 9,916 ft) on the Continental Divide near Chama. The lowest point is the San Juan River channel near the Four Corners at the boundary between the Navajo and Canyonlands sections of the Colorado Plateau (elevation about 4,700 ft.).

The only major perennial streams in the Navajo Section are the San Juan River, the Animas and La Plata rivers (which join the San Juan near Farmington), and the upper Rio Chama. The floodplains of these rivers are flanked by stepped sequences of fluvial terraces of Pleistocene age.

In the eastern part of the San Juan Basin, badlands are locally well developed on steep slopes carved on shaly sequences of late Cretaceous and early Cenozoic age. Partly vegetated aeolian sand sheets, with low eastnortheast-trending dune ridges, and small active dune fields form extensive caps on upland surfaces in the central part of the Navajo Section, particularly between the San Juan and Chaco Valleys.

The Acoma-Zuni Section, the southeastern subdivision of the Colorado Plateau, is a newly defined physiographic unit that includes the northern part of the area previously designated the Datil Section. The unit is bounded on the east by the Albuquerque Basin, a Rio Grande rift basin in the northern part of the Basin and Range Province. The Datil-Mogollon (transitional) Section lies to the south.

The Acoma-Zuni Section is characterized by extensive upper Cenozoic volcanics that form a discontinuous cover on erosional and constructional landforms typical of the neighboring Navajo Section. The northeastern Acoma-Zuni area is dominated by Mount Taylor, a composite stratovolcano of Pliocene age, and nearby basalt-capped mesas. Cabezon Peak at the northeast edge of the section is a particularly prominent plug-type volcanic neck. To the west, the elongate upwarp of the Zuni Mountains (maximum elevation 9,265 ft), with a core of Precambrian crystalline rocks, is flanked by hogback and cuesta belts that have dipslopes and scarps capped by Permian and Triassic limestone and sandstone.

Broad plains south and east of the Zuni uplift are covered with Quaternary basalt flows and dotted with numerous cinder and lava cones. The Malpais Lava Field south of Grants contains the McCarty's basalt flow, which is about 1,000 years old and is the youngest volcanic unit in the state.

The Acoma structural sag and adjacent Lucero Uplift in the southeast part of the section include prominent sandstone-capped mesas and buttes of the Acoma and Laguna reservations. Limestone- and sandstone-capped cuestas and benches of the Sierra Lucero area overlook the lower Rio Puerco Valley in the western Albuquerque Basin. As in the northern part of the section, many tablelands are capped with Pliocene basalt flows.

Much of the Acoma-Zuni Section is drained by the Rio San Jose, the major tributary to the Rio Puerco. Downstream from its headwaters in the Zuni Mountains and Malpais Lava Field the river has few perennial reaches. Most narrow, deeply entrenched valleys of the San Jose system are south and east of the Mount Taylor volcanic field; elsewhere major valleys of the San Jose system are commonly broad, but still well entrenched below upland areas. Pleistocene basalt flows cap river terraces in the lower San Jose Valley downstream from Laguna.

The Datil-Mogollon Section is part of a physiographic subdivision that is transitional between the Basin and Range Province and the Colorado Plateau. It is also a newly defined unit that includes the southern part of the area previously designated the Datil Section. This region of volcanic highlands extends into east-central Arizona and contains several large structural basins and block-faulted ranges. It is bounded on the east by basins of the Rio Grande rift, which are part of the Mexican Highland Section of the Basin and Range Province.

The Datil-Mogollon volcanic field is the dominant geologic feature in this section and lavas and tuffs are the main rock types. Major landscape units are erosional remnants of huge cauldron structures with
volcano-tectonic depressions and resurgent domes. There are also remnants of large stratovolcanoes, mainly composed of basaltic andesite. High tablelands are capped with tuffs, andesite, and basalt lavas, and volcanic-derived conglomeratic sandstones and mudstones.

The Datil-Mogollon Section also straddles the Continental Divide (6,650 to 10,000 ft elevation range). The area west of the divide is drained by perennial headwaters of the upper Gila system, including the San Francisco and Tularosa rivers. Canyon incision by these streams has resulted in the deeply dissected tableland topography of the upper Gila River basin.

Internally drained structural basins (bolsons) and valleys of major ephemeral streams (arroyos) draining to the Rio Grande are dominant features east of the Continental Divide. San Augustin Plains, the floor of the largest closed basin (minimum elevation 6,780 ft), was the site of pluvial Lake San Augustin. Maximum elevation of shoreline features is slightly higher than 7,000 ft.

The Basin and Range Province includes much of central and southwestern New Mexico, and it extends into adjacent areas of Arizona, Chihuahua, and Texas.

The Mexican Highland Section includes two large areas of basin-and range structure and topography separated by the valley of the Rio Grande. The Rio Grande rift depression coincides with the northern and eastern parts of the section. The Continental Divide crosses the bolson area west of the Rio Grande and is arbitrarily placed along the highest local drainage divides in the complex of internally drained basins between the Rio Grande and the Gila valleys.

Block-faulted mountains commonly have Precambrian cores overlain by Paleozoic sedimentary sequences. Sandia Peak (elevation 10,682 ft), the highest point in the section, is at the crest of tilted-fault block of this type. Organ Needle (elevation 9,012 ft) is the highest peak in the southern Mexican Highlands. Basin deposits which locally exceed 5,000 ft in thickness have several distinct basin-fill facies, including piedmont alluvium, fine-grained lake and playa sediments, coarse-grained river deposits, and aeolian (wind-carried) materials. Basalt fields are also locally extensive on basin plains; the youngest is the Carrizozo flow in the northern Tularosa Basin.

A number of the basin-floor depressions were occupied by perennial lakes during Pleistocene glacial-pluvial intervals. The largest late Pleistocene lakes, each about 200 square miles in area, were Lake Animas west of Lordsburg and Lake Otero in the Tularosa Basin west of Alamogordo. Large dune fields, including the White (gypsum) Sands of Tularosa Basin, are downwind from the pluvial-lake plains and younger playa depressions.

The Rio Grande flows through an alternative series of broad and narrow valley segments that coincide with major structural basins of the Rio Grande rift, each separated by bedrock uplifts. The valley for the most part is incised from 300 to 600 ft into upper basin fill and associated volcanics. The only major canyon reach is Whitewater Canyon, east of the Pajarito Plateau, where the river cuts through the thick basin sequence of the Cerros del Rio volcanic field.

The Gila River crosses the northwestern Mexican Highlands (north of Lordsburg) in a valley setting very similar to that along the Rio Grande. The low point of the Mexican Highland Section (about 3,700 ft) is at the Arizona border near Virden.

The Sacramento Section is characterized by high tablelands with broad, rolling summit plains; cuesta-form mountains, with eastward dipslopes and west-facing escarpments; and widely separated structural basins. Highlands, such as the Sacramento and Guadalupe mountains and Chupadera and Glorieta mesas, are capped with gently dipping limestone and sandstone of Permian age. Gypsum is commonly interbedded with limestone and sandstone sequences, and summit plains of tablelands and cuestas include extensive areas of karst depressions where dissolution of calcium sulfate and carbonate has taken place. Large limestone cave systems, such as Carlsbad and Fort Stanton caverns, are present in the Guadalupe and Sacramento highlands.

The Sierra Blanca igneous-intrusive and volcanic terrain is the highest part of the province. Sierra Blanca Peak (elevation 12,003) is the southernmost glaciated peak in the continental United States. Topographic relief between Sierra Blanca and the adjacent Tularosa Basin (twenty miles to the west) is about 7,600 ft, making this the area of greatest local relief in New Mexico. Other highlands formed by igneous-intrusive masses are the Capitan, Carrizo, Jicarilla, and Gallinas mountains.

The Estancia Basin, in the northwest part of the section (minimum elevation 6,050 ft), is a shallow structural basin, extensively modified by dissolution of gypsum, and by water and wind erosion. Basin fill is less
than 500 ft thick and contains lacustrine and aeolian deposits. Lake-shoreline elevations range up to about 6,350 ft. Holocene deflation has excavated numerous playa depressions, including Laguna del Perro in the basin floor. Small Pleistocene-lake basins and Holocene playas near Pinos Wells and Encino are located along an ancient spillway route from the Estancia Basin toward the ancestral Pecos Valley.

The Great Plains Province occupies the eastern third of New Mexico and includes parts of three sections. The Pecos Valley Section includes the terraced valleys of the Pecos and Canadian rivers and flanking piedmont plains and tablelands. Inner river valleys range from reaches with broad floors, occupied by floodplains and low terraces, to relatively shallow canyons. Elevation of the Pecos Valley floor ranges from about 5,300 ft near Anton Chico at the section’s northwest corner to 2,840 ft at Red Bluff Reservoir on the Texas border. The latter site is the lowest point in New Mexico.

Higher piedmont erosion surfaces west of the Pecos are cut on eastward-dipping Permian rocks and are transitional to surfaces in the Sacramento Section, highlands. Broad upland plains and tableland summits have caliche caprocks developed on veneers of upper Tertiary piedmont deposits.

The Pecos Valley Section extends southward and eastward into western Texas along the lower Pecos, Portales, and lower Canadian valleys. The Portales Valley east of Fort Sumner is a segment of the ancient upper Pecos-Brazos river valley that was abandoned by middle Pleistocene time. The High Plains borders are commonly marked by escarpments cut in sedimentary sequences with caliche caprocks. These features include Mescalero “Ridge” east of Roswell and “The Caprock” escarpment south of Tucumcari. The bold Canadian Escarpment forms the boundary with the Raton Section to the north.

Much of the Pecos Valley Section is underlain by Permian bedrock units composed of gypsiferous and saline evaporites, limestone and dolomite, mudstone and shale, and sandstone. Dissolution of evaporite and carbonate units is an active geomorphic process affecting landscape evolution in much of the region, and solution-subsidence depressions at a wide range of scales are common landforms. Several solution-subsidence basins southeast of Roswell have areas of many square miles. A stepped sequence of valley-border surfaces also flanks the inner valleys and canyons of the Pecos and Canadian rivers. These surfaces are inset below the high-level piedmont plains and reflect alternating intervals of valley incision and relative base-level stability during Pleistocene glacial-interglacial cycles. Quaternary wind-formed deposits mantle large areas of older valley-border surfaces east of the Pecos and north of the lower Canadian rivers.

Thick alluvial fills of late Tertiary and Quaternary age are present in broader central valley areas along the Pecos south of Santa Rosa, in the Canadian Valley northeast of Tucumcari, and in the Portales Valley. The Llano Estacado Section in New Mexico occurs as three separate areas that are western extensions of two major piedmont plateaus in the Panhandle region of Texas and Oklahoma. The plateau south of the Canadian Valley and the Caprock escarpment are designated the Llano Estacado or Staked Plains. In east-central New Mexico this area is bisected by the Portales Valley. The Staked Plains north of the Canadian Valley are also called the Panhandle subsection and are transitional westward to basalt-capped piedmont plateaus of the Raton Section. The Llano Estacado is characterized by a nearly flat to undulating surface with a slight southeastward gradient. Elevations range from about 5,000 ft at the northwest edge to 3,500 ft near Hobbs.

Alluvial and aeolian deposits of the Ogallala Formation, with a resistant caliche caprock, underlie much of the High Plains surface. The caprock zone of secondary carbonate accumulation is at or near the surface along plateau edges and in most of the Llano area south of the Portales Valley. Elsewhere the Ogallala is usually buried by sandy to clayey deposits. Surface drainage throughout the area is poorly developed; shallow valleys of ephemeral streams cross the High Plains only at wide intervals. The broad uplands between stream valleys are dotted with thousands of small, shallow depressions, many of which contain playas and have low arcuate dune ridges on their eastern (downward) margins. The dominant process involved in basin formation appears to be deflation. However, water erosion of basin sideslopes and dissolution of soluble constituents of underlying deposits may also play an important role in depression formation and enlargement.

The Raton Section is characterized by high piedmont plains, of both erosional and constructional origin. Extensive basalt flows protect many of the highlevel surfaces from erosion. Deep canyons of the Canadian and Cimarron river systems are cut below these piedmont-surface remnants in the southcentral and northeastern parts of the section. To the south, stripped structural plains are abruptly terminated by the Cana-
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dian Escarpment, which borders the Pecos Valley Section.

Some of the most striking features of the Raton Section are the numerous late Cenozoic volcanic centers, such as the andesitic Sierra Grande stratovolcano (8,720 ft) southeast of Raton, and the extensive plains and tablelands capped by basalt flows. High mesas near Raton, such as Johnson and Bartlett mesas, are capped by basalts that were emplaced during the period of High Plains surface development. Extensive younger basalts west of Clayton and Wagon Mound cap remnants of the High Plains surface and associated piedmont alluvial deposits. Basalt flows of Pleistocene age, such as the Maxon Crater, and older Capulin flows cap river terraces within the Mora, Canadian, and Dry Cimarron canyons. The youngest Capulin flow locally covers the floor of Dry Cimarron Canyon north of Folsom.

Sedimentary rocks, for the most part broadly folded and gently dipping, underlie much of the Raton Section. Erosion surfaces on these units include the highly dissected Park Plateau west of Raton and the Trinidad escarpment which overlooks broad central plains near Springer. Extensive surfaces, such as Rayado and Charette mesas, are capped by upper Tertiary basalts.

Much of the southeastern third of the Raton Section is characterized by broad tablelands capped by an extensive sandstone unit (Dakota-Mesa Rica). Tableland summits include the broad rolling plains of the Las Vegas Plateau west of the Canadian Canyon and more dissected mesa areas to the northeast between Ute Creek and Dry Cimarron valleys. A large High Plains outlier extending north from Mosquero is located between the Canadian Canyon and Ute Creek Valley. This constructional surface is mantled with piedmont alluvial deposits and has a caliche caprock.

Factors of Soil Formation

According to the Soils of New Mexico report (1978), the kind of soil that develops in any area is the result of the interaction of five soil-forming factors: climate, vegetation, parent material, topography, and time. The first two are called “active” factors because they act on the soil parent material as conditioned by topography over varying periods of time.

Climate and vegetation frequently are considered together because climate is the major determinant of vegetation. Soils of the high mountains of northern New Mexico are commonly leached, well developed, and acidic because precipitation is relatively high, temperatures are low, and the dominant vegetation is coniferous trees, which are best suited to the climatic and soil conditions. On the other hand, grasses and desert shrubs are dominant in the hot, dry desertic region. Here, the soils are not leached, are less developed, and are neutral or alkaline. Whether soil determines the kind of vegetation or whether vegetation determines the kind of soil is a much-debated point, but climate certainly is the deciding factor for both.

In New Mexico, temperature and precipitation are related principally to land elevation. For example, in the relatively short distance between the Tularosa Basin and the ski run on Sierra Blanca, temperatures drop, precipitation increases, the vegetation changes from grasses to trees, and the soils change from calcareous and weakly developed to acidic and strongly developed. The growing (frost-free) season varies from about 210 days at the lowest part of the state near Carlsbad to fewer than 100 days in the Sangre de Cristo Mountains of northern New Mexico. Desert grasses and shrubs are the dominant vegetation in the arid plains of the south, whereas alpine vegetation occurs above the timberline on high mountain peaks. Precipitation distribution patterns differ from eastern New Mexico to western New Mexico. In the east, precipitation is lowest in winter and highest in summer. In the west, precipitation is at a minimum in April and May and a maximum in July and August.

Parent material consists of the geologic material from which soils are developed. Soils on very young alluvium, such as in the valley of the Rio Grande or on the sand dunes of southern New Mexico, are essentially undeveloped, so their characteristics are similar to those of the parent materials. On the other hand, soils of the high mountains of northern New Mexico have characteristics that bear little relation to the parent material from which they developed. Climate and vegetation are the dominant soil-forming factors in humid areas.

Rocks of Cretaceous, Tertiary, and Quaternary ages dominate the surficial geology, but geologic formations dating as far back as Precambrian occur, mostly in the north-central part of the state. Evidence of volcanic activity can be seen throughout the state except in the southeastern quarter, where only sedimentary formations are found. Lava flows occurred as recently as about 1,000 years ago south of Grants. Limestone and sandstone are the principal sedimentary rocks for the state as a whole, but shale is locally important north and west of Tucumcari and in the northwest corner of the state.

Topography affects soils greatly. Thin, eroded soils are commonplace on steep slopes. In depressions, fine-textured, saline, poorly drained soils are a logical consequence of the topographical conditions. Soils on the south-facing slopes are subject to higher temperatures than their counterparts on the north sides of hills. The topography of the state is highly varied. The high plains of eastern New Mexico are relatively flat. The remainder of the state includes basins, plains, plateaus, mesas, mountains with their valleys, and floodplains.

The importance of time to soil formation arises from the fact that natural processes of soil development tend to reach an equilibrium which depends upon local environmental conditions. It takes thousands of years for a mature soil to develop from raw rock materials. The landscape of New Mexico is young, geologically speaking. Nearly all surficial deposits from which soils have developed have been affected by climatic changes occurring in the last million years. Many of them owe their characteristics to the soil-forming processes operating during and since the last glacial period.
Soil Classification

Soil scientists use several systems to classify soils. These deal with the soil as a natural body and consider the volume of soil affected by biological activity, which usually extends to a depth of several feet. One such classification lists the five soil orders in New Mexico as Aridisols, Mollisols, Entisols, Inceptisols, and Affisols. Aridisols are extensive in lower elevations over the southern two thirds of the state but are replaced in the cooler and moister higher elevations by Mollisols. Entisols occupy the Rio Grande Valley from Santa Fe south to the Texas Mexico border. The northern third of the state and the far eastern counties are dominated by Mollisols, Entisols, and Alfisols. Inceptisols are found in the highest elevations of the San Juan and Sangre de Cristo Mountains. Other materials of note include the gypsum sands of White Sands National Monument and the lavas of the Carrizozo, Grants, and other malpais (lava rockland).

Aridisols dominate the lower elevations of New Mexico. Aridisols lack necessary moisture for mesophytic plant growth for long periods. Thus, Aridisols are not suitable for dryland agriculture. During most of the year the soil water is held at tensions above the wilting point for most plants. Generally, the soil horizons (distinct layers of soil) were formed under a more moist regime, as during former pluvial periods. The surface horizon (layer) is usually low in organic matter content and is thus light in color. The Aridisols are often calcareous from the surface downward and have a secondary accumulation of calcium carbonate (lime) and/or gypsum in the subsoil. Soil textures range from loamy sands to clays and consistency ranges from soft to extremely hard. Most of the surface is bare much of the time and in many instances a surface gravel pavement has formed by deflation of the finer windblown particles. The Aridisols are important resources but are easily misused. Both wind and water erosion are a constant hazard. Under agriculture, special fertility problems can exist because of unavailable micronutrients resulting from a high pH. In general, however, the Aridisols have a high content of bases needed for plant growth.

Entisols can occur in any climate; however, most of these soils in New Mexico occur in an arid climate in association with Aridisols. Entisols have been exposed to the soil-forming processes for such a short time that no major soil horizons have formed. Examples of Entisols are soils on floodplains or soils frequently moved by wind erosion. They also occur on moderate to steep slopes where bedrock is shallow. In general, the Entisols express the properties of the parent material with little change. Their nutrient supplying capacity is generally high. Salinity and sodicity may be limited. Erosion hazard can be high, especially on the soils derived from wind-blown sediments. Most of the soils of the Rio Grande Valley in agriculture are Entisols.

Inceptisols exhibit the initial sign of soil development: a color change in the subsoil. They occur in areas of more rainfall than those yielding Aridisols. In New Mexico this is mainly in mountains which receive more than 12-14 inches of rainfall. The Inceptisols are young, occurring mainly on steep slopes where erosion removes weathered sediments. They also occur in areas dominated by volcanic pumice where insufficient time has passed to allow the formation of a more weathered soil. In New Mexico, their base-supplying capacity is generally high.

Affisols also occur in climates more moist than those yielding Aridisols. Alfisols occur in the mountains of northern New Mexico and on the plains in eastern New Mexico. Organic matter accumulation in the surface horizon is greater than in Aridisols but is still low enough that the color is either light or dark to only shallow depths. Alfisols have been subjected to soil formation processes for long enough that clay has translocated and accumulated in the subsoil. Many of the Alfisols have sufficient moisture and nutrient supply to support dryland agriculture.

Mollisols are characterized by deep, dark surface horizons of high organic matter content. They occur in areas of New Mexico with more than 12-14 inches of rainfall (similar in rainfall to areas with Inceptisols and Alfisols). Mollisols are dominantly grassland soils but do occur in the forests of southern New Mexico where the base status is high and grass is the dominant understory. Mollisols are very fertile soils with a high supply of nutrients. Lime often accumulates in the subsoil. Mollisols, like most soils in New Mexico, are fragile when misused. Water erosion hazard is high in some areas. Most of the Mollisols are used to support grazing some in eastern New Mexico are used for crop production.

Vegetation: Riparian and Montane; Plateau, Basin, and Plains

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The complex vegetation composition of New Mexico is the consequence of many habitats resulting from a broad range of elevations from about 2,800 ft in the southeastern corner of the state to more than 13,150 ft at the summit of Mt. Wheeler in the Sangre de Cristo Mountains of the north-central part. The flora variety is also related to the great geological diversity and complex topography, and to the differences in precipitation throughout the state. The rainfall amounts range from as much as 35-40 inches in the northern mountains to less than 8 inches in the southern desert areas. The natural vegetation of New Mexico has also become locally modified by the effects of disturbance, including long-term human habitation, extensive overgrazing, surface and subsurface mining, and the introduction of species from other areas.

The vegetational assemblages of New Mexico are divided into two groups for discussion and mapping purposes. Group I represents associations of the Coniferous Woodland, Montane Shrub, Montane Grassland, Mixed Conifer, Subalpine, Alpine-Tundra, and Riparian vegetation. Group II includes associations of the Chihuahuan Shrub, Chihuahuan Grassland, Great Basin Shrub, Great Basin Grassland, and Plains and Prairie Grassland.

Riparian vegetation is primarily confined to a relatively narrow band adjacent to water courses and is most apparent along major streams. Plants common to this assemblage include willows of several species, cottonwoods, ash-leaved maple, alder, and birch. In southern areas the sycamore, New Mexico olive, and walnut are found along with many other shrubs and forbs. Many naturalized taxa tend to be very common in riparian areas, especially in floodplain zones along major streams. Plants of this zone gradually merge with those of the adjacent vegetation zones.

Montane habitats are characteristic of large areas of New Mexico, typically at elevations from 6,000 to more than 13,000 feet. The vegetation represented here is found in several recognizable floristic zones, including coniferous woodland, montane shrubland, montane grassland, mixed conifer, spruce-fir, and alpine-tundra zones.

The Coniferous Woodland is a characteristic feature of the lower slopes of montane areas throughout New Mexico, mostly at elevations from 5,500 to 7,000 ft. This zone merges with grassland at its lower elevation limits and with the mixed conifer association at the higher limits, where pinyons and junipers are gradually replaced by ponderosa pine, which becomes the dominant tree species. In some places the coniferous woodland gives way to a montane shrub association, where some junipers may occur but where the dominant vegetation is composed mostly of deciduous shrubs. Sometimes dense thickets are formed. The general aspect of the coniferous woodland is that of an open stand of the dominant conifers interspersed with species of grasses and a few forbs in the open areas. Because of the relatively dry site conditions, forbs are never abundant in this zone. When montane shrubland appears at this elevation, it often represents a natural replacement for coniferous areas which have been destroyed by fire.

Coniferous woodland vegetation with pinyon and juniper dominant is an assemblage characterized by large populations of either the pinyon or juniper or both. Where pinyon is the primary dominant, juniper is a secondary dominant, sometimes without additional woody species present. Herbaceous plants may be numerous, depending on edaphic factors and elevation. On some sites, Gambel oak may be dispersed throughout the association; on other sites, scattered big sagebrush may be more common. Where juniper is the primary dominant, pinyon (often referred to as Mexican pinyon in the southwestern part of the state) is usually the secondary dominant. Oaks, either the wavyleaf or other species, may be common. Sometimes big sagebrush may be scattered throughout the association. At some locations in the Great Basin region the primary dominant, juniper, has big sagebrush as a secondary dominant; here, pinyon tends to be absent.

At various elevations in both the mixed conifer and spruce-fir zones there are often extensive open grasslands or meadows. This Montane Grassland vegetation is represented by an extensive herbaceous understorey, including many species of grasses as well as a few species of shrubs.

Montane grassland vegetation with fescue dominant forms open grasslands at elevations of approximately
8,000-10,500 ft and is dominated by Thurber fescue at higher elevations and by Arizona fescue at lower elevations. Where dominant, Thurber fescue is associated with Arizona fescue as a secondary dominant; when Arizona fescue is dominant, it tends to be associated with mountain muhly. Bluegrass, various sedges, brome, and some herbs, such as cinquefoil, occur at the higher elevations in this zone. On lower, warmer sites, sideoats grama may be found. These areas occur mostly in Mora, Taos, Sandoval, and Rio Arriba counties.

Montane grassland vegetation with mountain muhly and pine dropseed dominant appears as an open, more or less parklike grassland at intermediate elevations. In addition to the dominant taxa, other grasses such as junegrass, squiretail, and sideoats grama, among others, occur. This assemblage is found primarily in Rio Arriba County. At higher elevations, especially in the subalpine region, sedges, bluegrass, tufted hairgrass, and several forbs occur in varying amounts.

The easily discernible Mixed Conifer zone begins at approximately 7,000 feet and extends upward to about 9,000 feet in elevation. Dominants in this zone include both ponderosa pine and Douglas fir. Other conifers, such as white fir and Rocky Mountain juniper, are also found here. The lower elevations in this zone are marked by a conspicuous abundance of ponderosa pine which gradually, with increasing elevation, begins to share its dominant status with Douglas fir until, at the upper limits of this zone, Douglas fir may become dominant.

Mixed conifer vegetation with ponderosa pine dominant includes several recognizable associations. Among these are the ponderosa pine associations with Rocky Mountain juniper in northern New Mexico (especially characteristic of areas of Rio Arriba County), with a shrubby understory of wavyleaf oak, sumac, or mountain mahogany; ponderosa pine in association with Gambel oak at the lower elevations, with a characteristic understory similar to that of the ponderosa pine/Rocky Mountain juniper combination; and ponderosa pine associated with Douglas fir at about the 8,000-foot level, along with an understory of shrubs such as snowberry, mountain spirea, currants, and a few grasses including species of fescue and brome. In some areas ponderosa pine may exist in nearly pure stands.

Mixed conifer vegetation with Douglas fir dominant is widespread in the higher mountains of New Mexico. The upper part of this zone is represented by Douglas fir in association with Engelmann spruce. At lower elevations, Engelmann spruce is replaced by ponderosa pine. Between the mixed conifer zone and the alpine-tundra zone, there is an extensive, heavily forested region dominated by Engelmann spruce and subalpine fir. Frequently the conifer stands are so dense that understory vegetation is relatively sparse.

Spruce-fir vegetation with Engelmann spruce dominant is typically found between 9,000 and 12,000 feet in elevation and is often referred to as the subalpine region. The largest extent of this association is located in north-central New Mexico and is dominated by Engelmann spruce with secondary dominants represented by subalpine fir and corkbark fir and scattered stands of Douglas fir.

Grassland glades are scattered throughout the spruce-fir zone. Numerous forbs are found here, along with several species of grasses and, in this area, sedges begin to become an important feature of the ground cover. Sedges become increasingly important at higher elevations, both in numbers of species and density and in value as a grazing and forage resource. In many places the original native species in these forest glades have been largely replaced by species other than those typical of these areas.

Throughout this zone large stands, often thousands of acres, of aspen form a major broadleaf deciduous tree community. This community, usually of relatively short duration, is in many cases an example of a stage in secondary succession following a major disturbance such as fire.

Above the upper limits of sustained tree growth lies the Alpine-Tundra zone, represented by a relatively small fraction of the montane areas of New Mexico. This zone normally begins at approximately 12,000 feet and extends upward to the summit of the high peaks. The boundaries between this zone and the usually heavily forested spruce-fir zone are marked by a scattering of lowgrowing, dwarfish, gnarled, usually windtrained spruce trees with the open areas populated by numerous species of sedges, species of grasses including tufted hairgrass, members of the pink family (Arenaria and Silene), caespitose phlox, saxifrages, and alpine cover. Alpine willows and several species of composites are also present in varying amounts. Although several recognizable communities occur in this zone, depending on the degree of slope, exposure, and depth of soil, the floristic composition of the alpine-tundra zone is relatively uniform.

The second grouping of New Mexican vegetational assemblages, extending over the desert, basins, and
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plains (and therefore the larger part) of the state, includes associations of the Chihuahuan Shrub, Chihuahuan Grassland, Great Basin Shrub, Great Basin Grassland, and Plains and Prairie Grassland.

Chihuahuan Shrub vegetation with creosote bush dominant is characteristic of desert regions of southern New Mexico and extends northward along the valley of the Rio Grande to Bernalillo County. In some areas creosote bush shares dominance with tarbush to form a dispersed overstory. On other sites tarbush is essentially absent and bush muhly becomes more prominent. Other grasses, including three-awn, fluffgrass, tobosa, and black grama, may be associated, and subshrubs such as yucca and snakeweed may occur in varying amounts. Among forbs, probably the most prominent species is desert marigold.

Chihuahuan shrub vegetation with acacia dominant association occurs mostly in southeastern and southwestern New Mexico and is usually characterized by catclaw acacia along with mesquite. Most of these sites are scattered and are often too small to be definitively mapped. Probably the largest continuous association of this kind occupies the area directly west and southwest of Carlsbad and extends into Mexico. Various grasses are also common here.

Chihuahuan shrub vegetation with fourwing saltbush dominant is usually associated with a scattering of mesquite, creosotebush, tarbush, coldenia, and iodinebush. Dominant grasses of the understory include either alkali sacaton or tobosa; these taxa are commonly associated with vine-mesquite, burrogras, saltgrass, sand dropseed, and gyp grama. This association is chiefly confined to desert areas of southern New Mexico, areas bordering the northern, eastern, and southern borders of White Sands, the Playas Lake area of Grant County, north-central Hidalgo County, and southeastern Socorro and southwestern Lincoln counties.

Great Basin Shrub vegetation with big sagebrush dominant is characterized by a scattering of Colorado pinyon and juniper with the big sagebrush. In the open spaces, common grasses are sand dropseed, blue grama, alkali sacaton, galleta, and western wheatgrass. This association is located mostly between 6,000 and 6,500 ft in western Taos, southeastern Rio Arriba, and northeastern Sandoval counties.

Great Basin shrub vegetation with saltbush dominant is an assemblage where dominance is usually shared by several species of saltbush, including four-wing, shadscale, and Nuttall saltbushes. On open slopes and mesas, pinyon, juniper, antelope brush, and serviceberry may be scattered and in flats greasewood may be locally abundant. Principal grasses include Indian ricegrass, galleta, blue grama, sideoats grama, alkali sacaton, and three-awn. This association is characteristic of sites throughout much of San Juan County between 6,000 and 6,500 ft, in western Sandoval, northern and eastern McKinley, and northwestern Bernalillo counties, and also an area of central Catron County.

Chihuahuan Grassland vegetation with burrograss dominant is an open grassland dominated by burrograss, usually containing significant amounts of tobosa, and to various degrees scatterings of fluffgrass, gyp dropseed, and gyp grama. Occasionally the boraginaceous subshrub, coldenia, will occur. This association extends from central Chaves County to central Eddy County and occurs in south-central Eddy County but does not extend into Mexico.

Chihuahuan grassland vegetation with grama grass dominant is composed of several dominant grama grasses, including black, blue, hairy, or sometimes sideoats grama in association with threeawn or tobosa at some localities and curly mesquite or bush muhly at others. Sometimes sand dropseed or burrograss occur as well as a scattering of cacti, juniper, or creosote bush.

Chihuahuan grassland vegetation with black grama dominant is dominated by black grama in conjunction with several species of dropseed and an occasional yucca on some sites, but in conjunction with bush muhly and a scattering of creosote bush on other sites. Species of cacti also occur at many of these sites and, in sandy areas, sand sagebrush appears. This association is scattered throughout much of the Chihuahuan Desert region.

Chihuahuan grassland vegetation with dropseed and Indian ricegrass dominant is typically found on sandy sites and dominated by several species of dropseed, such as sand, mesa, and spike dropseed, in conjunction with ricegrass. Scattered shrubs include yucca and sand sagebrush. This association is relatively uncommon, occupying several sites in the central Rio Grande Valley including parts of Bernalillo, Valencia, and Socorro counties.

Chihuahuan grassland vegetation is also with sacaton and tobosa dominant. Giant and alkali sacaton, along with tobosa, are the important representatives here.
This association is found in a few localities in Sierra, Lincoln, and Otero counties.

Great Basin Grassland vegetation with Indian ricegrass and galleta dominant is associated with various other grasses, including blue grama, sand dropseed, various three-awns, and sometimes sideoats grama. There may be a scattering of big sagebrush, Mormon tea snakeweed, and juniper on some sites. This association is scattered throughout the northwestern and west-central counties.

Great Basin grassland vegetation with big sagebrush dominant is found in conjunction with Indian ricegrass, sand dropseed, galleta, three-awn, blue grama, or sometimes western wheatgrass. Rabbitbrush may be locally abundant and populations of snakeweed occasionally occur. This association is mostly found in San Juan, Sandoval, and Taos counties.

Great Basin grassland vegetation also occurs with saltbush and alkali sacaton dominant. At least two species of saltbush are found here, usually fourwing and shadscale, along with alkali sacaton and lesser amounts of other grasses such as blue grama and western wheatgrass. Populations of rabbitbrush may occur sporadically. This association is found throughout the Great Basin region.

There is a large area of Great Basin grassland vegetation with grama grasses and western wheatgrass dominant. Several species of grama grasses are common here and include sideoats, blue, black, and hairy grama in conjunction with western wheatgrass. Other grasses found in various but lesser amounts are muhly, vine-mesquite, or three-awn and sometimes small amounts of Indian ricegrass or junegrass appear. This association is most common in Valencia, Cibola, and Catron counties.

Plains grassland vegetation with sideoats grama dominant is another complex assemblage of associations with sideoats; grama typically dominant and associated, depending upon the association, with blue grama, black grama, curly mesquite, Metcalf muhly, and feathergrass. Less common grass species are galleta, sand dropseed, buffalograss, three-awn, plains bristlegrass, tridens, and western wheatgrass. Shrubby plants such as snakeweed, yucca, sotol, winterfat, cacti, and sometimes scrub oaks may occur in varying amounts. Also, junipers may be locally common. This assemblage is found throughout the Great Plains region of New Mexico.

There is a small area in the state of Plains grassland vegetation with buffalograss dominant. This taxon usually shares dominance with blue grama in this reasonably well-marked short-grass association, with the dominants interspersed with varying amounts of vine-mesquite, tobosa, galleta, and alkali sacaton. Mesquite sometimes also occurs in limited amounts, usually in localized populations. This association is most common in extreme eastern New Mexico, primarily in eastern Quay County.

Plains grassland vegetation with four-wing saltbush and sacaton dominant usually includes the dominants with varying numbers of other taxa interspersed. Sometimes alkali sacaton occurs in nearly pure stands. At other sites, four-wing saltbush is a strong primary dominant with minor grass components interspersed. This assemblage occurs mostly in relatively small areas of Catron, Socorro, Torrance, and Quay counties.

Prairie Grassland vegetation with blue stem dominant is primarily a tallgrass assemblage with little blue stem and often sand blue stem as dominants. On some sites sand sagebrush is a codominant and silver blue stem, dropseed, sideoats and blue gramas, Indian ricegrass, switchgrass, and yuccas may occur in varying amounts. On other sites, shinnery oak is a secondary dominant and is usually associated with giant and sand dropseed, sideoats and black grama, bristlegrass, and yucca. On still other sites, sideoats grama will be a secondary dominant and associated species may include hairy grama and a scattering of juniper. This assemblage is found in several of the eastern counties, from De Baca County eastward beyond the border.
