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About the Geologic Map in the National Atlas of the United States of America

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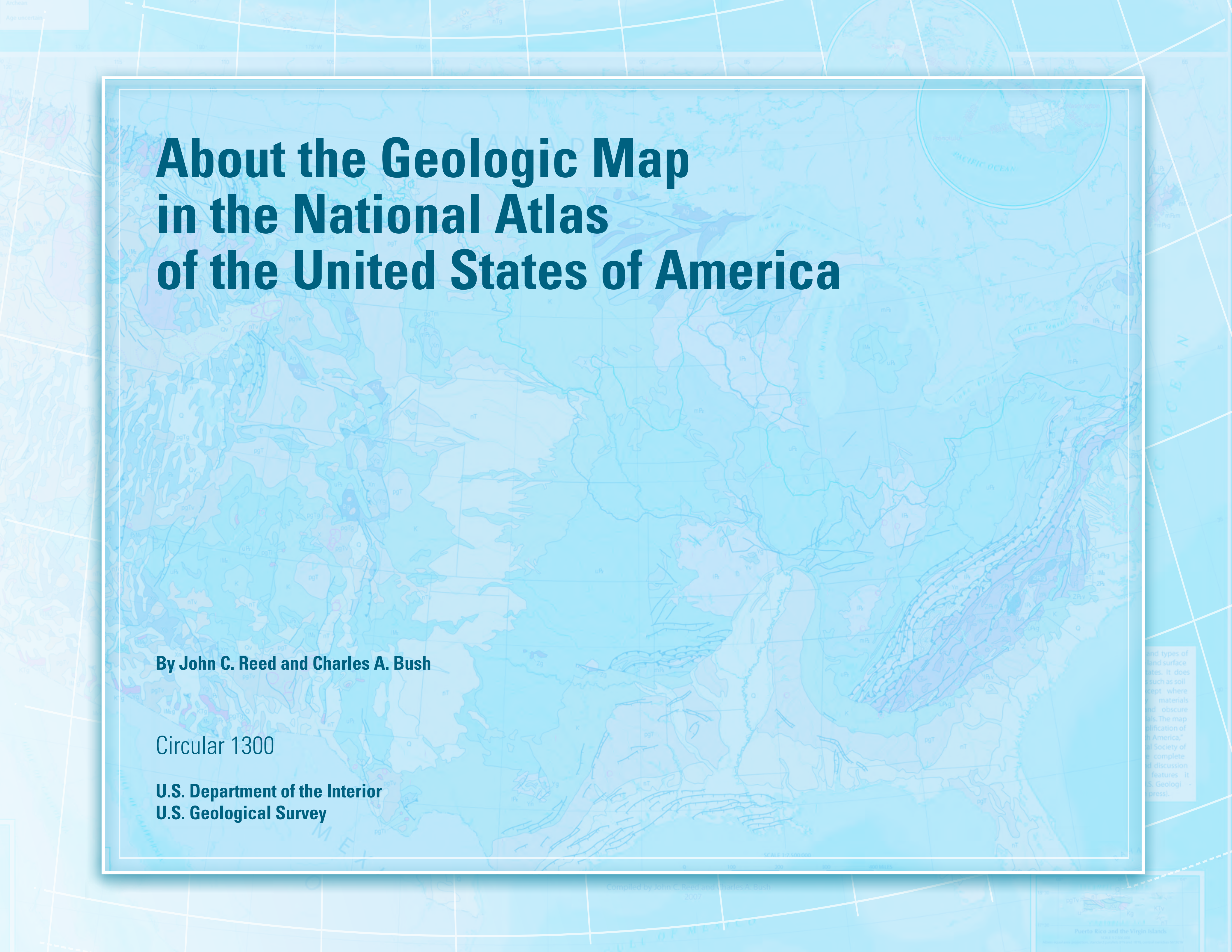

About the Geologic Map in the National Atlas of the United States of America

By John C. Reed and Charles A. Bush

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About the Geologic Map in the National Atlas *of the* United States of America

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Introduction

The geologic map in the National Atlas of the United States of America shows the age, distribution, and general character of the rocks that underlie the Nation, including Alaska, Hawaii, Puerto Rico, and the Virgin Islands (but excluding other small island possessions). (The *National Atlas of the United States* can be accessed at URL http://nationalatlas.gov/natlas/Natlasstart.asp.) The map depicts the **bedrock**[1] that lies immediately beneath soils or **surficial deposits** except where these deposits are so thick and extensive that the type of bedrock beneath them can only be inferred by deep drilling or geophysical methods, or both. Thus, it does not show the extensive glacial deposits of the North Central and Northeastern States, the deep **residuum** of the Southeastern and South Central States, the relatively thin **alluvium** along many major rivers and basins, and extensive **eolian** deposits on the high plains. However, it does show, in a general way, the thick alluvial deposits along the lower Mississippi River and on the Atlantic and Gulf Coastal Plains, and in the deep basins of the western cordillera.

The rocks are classified as either **sedimentary, volcanic**, **plutonic**, or **metamorphic**, and their **geologic ages** are given in terms using a simplified version of the 1999 Geological Society of America **geologic time scale** (fig. 1). In some places rocks depicted as sedimentary are interlayered with volcanic rocks, including **tuff, volcanic breccia**, and **volcanic flows.** Conversely, many of the rocks shown as volcanic include interlayered sedimentary rocks. Plutonic rocks are classified by age and as **granitic, intermediate, mafic**, or **ultramafic**, but no similar classification has been attempted for the volcanic rocks in this version of the map. Where sedimentary or volcanic rocks have been metamorphosed but still retain clear evidence of their **depositional age** and origin, the extent of the metamorphism is shown by a pattern. Where the metamorphism has been so intense that the rocks bear little resemblance to the rocks from which they were derived, they are mapped as **gneiss,** but the age given is generally the age of the original rocks.

The map in the National Atlas is a generalization of a new geologic map of North America that has recently been published by the Geological Society of America. The original compilation was prepared at a scale of 1:2,500,000 for publication at a scale of 1:5,000,000. This generalized version is intended for viewing at scales between about 1:10,000,000 and 1:7,500,000. Figures 2 and 13 are index maps showing the various geologic provinces described in the following section. Figure 2 shows provinces in the conterminous United States; figure 13 shows those in Alaska.

EON	ERA		PERIOD		MILLIONS OF YEARS AGO
Phanerozoic	Cenozoic		Quaternary		1.8
			Tertiary	Neogene	23.8
				Paleogene	65
	Mesozoic		Cretaceous		144
			Jurassic		206
			Triassic		248
	Paleozoic	upper*	Permian		290
			Pennsylvanian		323
		middle*	Mississippian		354
			Devonian		417
			Silurian		443
		lower*	Ordovician		490
			Cambrian		543
Proterozoic	Late Proterozoic Middle Proterozoic Early Proterozoic				2,500
Archean	Late Archean Middle Archean Early Archean				3,800?
pre-Archean					

Figure 1. Geologic time scale. Asterisk (*) denotes informal unit.

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[1] Terms in bold type are defined in the Glossary.

Geologic Provinces

Conterminous United States

The conterminous United States occupies a significant part of southern North America, and its complex geology reflects the complex geology of the continent (fig. 2). The nucleus of the continent is a stable block of metamorphic and igneous rocks assembled from about half a dozen plates of **continental crust** at various times during the **Precambrian**. Most of this block of continental crust, called the North American **craton**, has remained stable during much of subsequent geologic time. However, parts of the eastern margin of the craton were deformed and metamorphosed during formation of the Appalachian mountain system, and extensive parts of the craton in the west have been affected by folding, faulting, and uplift during formation of the Cordilleran mountain system. Large parts of the craton were blanketed by sediments deposited in shallow seas that washed across it during the **Paleozoic** and **Mesozoic** and by materials eroded from highlands that developed along its margins from time to time. For descriptive purposes the area of the conterminous United States can be divided into four principal provinces: (1) Central Interior Region, which comprises the craton and its veneer of little-disturbed sedimentary rocks; (2) the Appalachian and Ouachita mountain systems, which border the craton on the east and south; (3) the coastal plains of the Southern and Southeastern States, which are composed of Mesozoic and **Tertiary** rocks that lap onto the southeastern margin of the Appalachians, largely cover the Ouachita mountain system, and lap directly onto the interior lowlands of the Central Interior Region in the Mississippi Valley; and (4) the Cordilleran mountain system, which flanks the craton on the west and extends to the Pacific Coast. Each of these can be further divided into subprovinces and belts that share similar geologic histories and display similar geologic features.

Central Interior Region

The Central Interior Region extends from the western foothills of the Appalachians to the eastern front of the Rocky Mountains, and from the Canadian border south to the northern limit of the Gulf Coastal Plain. Thus, it encompasses nearly half of the area of the conterminous United States.

Canadian Shield

Precambrian rocks shown on the map in Minnesota and Wisconsin are part of the southern margin of the Canadian Shield, the vast area in which the Precambrian rocks that form the North American craton are exposed at the surface. These rocks are widely exposed in central Canada, but in the United States they are poorly exposed beneath the extensive cover of **Quaternary** glacial deposits (not shown on this map). The **Archean** gneiss (unit An) and granite (unit Ag) mapped in northwestern Minnesota are among the oldest rocks of the shield; some are as old as 3.6 billion years. The gneiss represents highly metamorphosed volcanic and sedimentary rocks that accumulated in or near **volcanic arcs** during the early stages

Figure 2. Index map showing geologic provinces and subprovinces in the conterminous United States. Heavy red lines show boundaries between major provinces; medium-weight blue lines show boundaries of subprovinces. Pink lines show smaller subdivisions, and in some places dashed pink lines show minor subdivisions. Lines are dashed where boundaries are concealed by younger deposits. Pink stipple shows early and mid-Tertiary volcanic provinces; blue stipple shows late Tertiary and Quaternary volcanic provinces and subprovinces. Small subdivisions and geologic features mentioned in the text are identified by circled letters and numbers. Note that the numbers and letters apply only within a particular province or subprovince and may be repeated in other subprovinces to identify different features.


CANADA
CORDILLERAN MOUNTAIN SYSTEM
ACCRETION- AND SUBDUCTION-RELATED TERRANES OF THE WESTERN CORDILLERA
SAN ANDREAS FAULT
Ⓐ
Ⓑ
Ⓒ
Ⓓ
Ⓔ
Ⓕ
Ⓖ
Ⓗ
Ⓘ
①
②
③
COLUMBIA RIVER PLATEAU
OREGON PLATEAUS
SNAKE RIVER PLAIN
IDAHO BATHOLITH
ROCKY MTS FOLD AND THRUST BELT
BOULDER BATHOLITH
ABSAROKA VOLCANIC FIELD
LARAMIDE ROCKY MTS
④
⑤
⑥
⑦
⑧
⑨
SIERRA–WASATCH VOLCANIC FIELD
BASIN AND RANGE PROVINCE
GREAT BASIN SUBPROVINCE
SONORAN SUBPROVINCE
SAN JUAN VOLCANIC FIELD
COLORADO PLATEAU
RIO GRANDE RIFT
MOGOLLON-DATIL VOLCANIC FIELD
DAVIS MOUNTAINS VOLCANIC FIELD
MARATHON UPLIFT
LLANO UPLIFT
WILLISTON BASIN
POWDER RIVER BASIN
BLACK HILLS UPLIFT
DENVER BASIN
OGALLALA APRON
CENTRAL INTERIOR REGION
INTERIOR LOWLANDS
CANADIAN SHIELD
OUACHITA MOUNTAIN SYSTEM
OZARK UPLIFT
ILLINOIS BASIN
MICHIGAN BASIN
CINCINNATI ARCH
NASHVILLE DOME
ADIRONDACK UPLIFT
APPALACHIAN BASIN
SEDIMENTARY APPALACHIANS
CRYSTALLINE APPALACHIANS
APPALACHIAN MOUNTAIN SYSTEM
ATLANTIC COASTAL PLAIN
MISSISSIPPI EMBAYMENT
GULF COASTAL PLAIN
COASTAL PLAIN PROVINCE
FLORIDA PENINSULA
MEXICO
SCALE 1:7,500,000
0 100 200 300 400 MILES
0 100 200 300 400 500 600 KILOMETERS
Albers equal-area projection, standard parallels 29°30'N and 45°30'N, central meridian 96°W
Compiled by John C. Reed and Charles A. Bush
2007

of formation of the craton. The granite intruded the sedimentary and volcanic rocks during their deposition or eruption or shortly thereafter.

The Early **Proterozoic** volcanic and granitic rocks (units Xv and Xg) shown in Wisconsin are part of a belt of island arcs added to the southern edge of the craton about 2.5 billion years ago. The Early Proterozoic sedimentary rocks (unit X) in northern Wisconsin and south-central Minnesota represent materials eroded from this newly added arc and deposited on top of the Archean rocks.

Finally, the Middle Proterozoic volcanic and sedimentary rocks (units Yv and Y) in southern Minnesota and northern and western Wisconsin fill a fault-bounded trough, the Midcontinent **Rift**, that formed about 1,000 million (1 billion) years ago. The rift lies beneath Paleozoic sedimentary rocks in southern Minnesota but can be traced southward beneath the covering rocks in drillholes and by **gravity** and **magnetic anomalies** all the way to central Kansas.

Interior Lowlands

South of the Canadian Shield the Precambrian basement rocks of the craton are largely mantled by a blanket of flat-lying sedimentary rocks that is generally a few hundred to thousands of feet thick. In the eastern and central parts of the lowlands the exposed sedimentary rocks are largely of Paleozoic age; in the western part of the lowlands the exposed rocks are chiefly Mesozoic and Tertiary. Most of the strata in the eastern part of the lowlands are **limestone**, **shale**, and **sandstone** formed from sediments deposited in shallow seas that periodically washed over the craton during the Paleozoic. However, some are shale, sandstone, and conglomerate composed of materials shed from the exposed parts of the craton or from the bordering Appalachian highlands. The broad areas of Cretaceous rocks in the western parts of the lowlands are mostly shale, **siltstone**, limestone, and sandstone formed from sediments deposited in a shallow seaway that extended across the craton from the present position of the Gulf of Mexico to the Arctic Ocean at that time. The Tertiary rocks along the western margin of the central lowlands are chiefly conglomerate, sandstone, and siltstone intermixed with **volcanic ash** deposited on land in basins and as thin veneers on the Cretaceous rocks during the rise of the Rocky Mountains.

The continuity of the sedimentary blanket is broken by a number of subcircular domes in which older rocks are exposed at the surface and subcircular to elongate basins in which younger strata are preserved. Commonly, sedimentary layers surrounding these features thin toward the uplifts and thicken toward the basins, this pattern suggesting that these features formed over long periods. Some of the principal features of the central interior lowlands are described below:

The Adirondack Uplift is a dome that exposes Middle Proterozoic metamorphosed sedimentary rocks (unit Y), gneiss (unit Yn), and plutonic rocks, including granite (unit Yg) and **anorthosite** (unit Ya) in its core. The dome is surrounded by **lower Paleozoic** rocks (unit lPz) that dip gently away from it in all directions.

The Cincinnati Arch and Nashville Dome are broad, elongate uplifts in which lower Paleozoic rocks (unit lPz) are exposed in the cores and **middle Paleozoic** rocks form the flanks (unit mPz).

The Ozark Uplift is a broad, gentle dome in which lower Paleozoic rocks (unit lPz) are extensively exposed in the center and middle Paleozoic rocks (unit mPz) form the flanks. **Basement rocks**, chiefly Middle Proterozoic granite (unit Yg) and rhyolite (unit Yv) are exposed locally beneath the lower Paleozoic strata in the core.

The Llano Uplift, a dome in central Texas, exposes a core of Middle Proterozoic rocks (units Yg, Yn) similar to those in the Adirondack Uplift surrounded by lower Paleozoic strata (unit lPz) and around its western, southern, and eastern margins by **Cretaceous** strata (unit K).

The Black Hills Uplift is a gentle, slightly elongate dome with a core composed largely of Early Proterozoic gneiss (unit Xn) and surrounded by middle Paleozoic (unit mPz), lower Mesozoic (unit lMz), and Cretaceous strata (unit K).

The Marathon Uplift in western Texas exposes folded and faulted lower Paleogene rocks (unit lPz) like those in the Ouachita Mountains (see below) and less deformed upper Paleogene rocks (unit uPz) that are tilted northward beneath Cretaceous strata (unit K) surrounding the uplift and that are themselves warped into a broad dome.

The Appalachian Basin is an elongate basin extending along the southeastern margin of the interior lowlands, adjacent to the main part of the Appalachian mountain system. Basement rocks along the trough of the basin are as much as 16,000 feet below sea level, and the basin is filled with middle and upper Paleozoic sedimentary rocks (units mPz, uPz), most of them representing materials eroded from the rising Appalachian highlands to the southeast. The upper Paleozoic rocks in the trough of the basin are chiefly sandstone, shale, and **conglomerate**, but they include many thick and continuous coal beds that constitute more than half of the bituminous coal reserves of the United States.

The Michigan Basin is a saucer-shaped depression in which the basement rocks are as much as 16,000 feet below sea level. Drilling shows that the lower and middle Paleozoic strata (units lPz, mPz), which are only about 300 feet thick in adjoining areas, thicken to thousands of feet in the center of the basin, which indicates that the basin was subsiding as these rocks were being deposited. The center of the basin is occupied by lower Mesozoic (**Jurassic**) rocks (unit lMz), the only occurrence of rocks of this age in the eastern part of the interior lowlands.

The Illinois Basin is a shallow, elliptical basin filled with **upper Paleozoic** rocks (unit uPz) beneath which basement rocks are downwarped to depths of more than 10,000 feet.

The Williston Basin and the Powder River Basin are irregular **downwarps** beneath which basement rocks are depressed to about 13,000 feet below sea level. At depth these basins contain somewhat thickened sections of Paleozoic and lower Mesozoic strata, but near the surface the basins are defined by downwarped Upper Cretaceous (unit K) and **Paleogene** (unit pgT) rocks. The Paleogene rocks are chiefly shale, sandstone, and conglomerate derived from the rising Rocky Mountains to the west. In the Powder River Basin they contain thick beds of low-sulfur subbituminous and bituminous coal.

The Denver Basin lies at the western edge of the interior lowlands, immediately adjacent to the eastern front of the Rocky Mountains. The deepest part of the basin is near its western edge, where basement rocks are as much as 7,000 feet below sea level (the elevation of the land surface there is about 5,000 feet above sea level). Sedimentary beds along the western flank of the basin slope steeply toward the basin or stand vertically, in contrast to their gentle slopes into the basin on the eastern, northern, and southern flanks. The basin is largely filled with Upper Cretaceous rocks (unit K), which reach a thickness of more than 5,000 feet. Upper Paleozoic and lower Mesozoic rocks beneath them are only slightly thicker than they are on the outer flanks of the basin. The youngest strata in the basin are Paleogene sedimentary and volcanic rocks that were deposited during initial uplift of the neighboring Laramide Rocky Mountains.

The Ogallala Apron is a broad, flat expanse of gravel, sand, and silt deposited by streams flowing eastward from the southern Rocky Mountains during rapid regional uplift during the **Neogene**. These stream-laid deposits (unit nT) make up the Ogallala Formation, one of the most important aquifers in the Western United States, which supplies ground water used for extensive irrigation in the High Plains of western Texas, Oklahoma, Colorado, Kansas, and Nebraska. The Ogallala originally formed a continuous, east-sloping apron that extended from the mountains at least 400 miles to the east. Downcutting by streams has dissected the apron so that the underlying Cretaceous and older rocks are exposed along major river valleys. Along much of the mountain front the Ogallala Apron is separated from its mountain sources by erosion along the Pecos, Canadian, Arkansas, and South Platte Rivers and their tributaries.

Appalachian and Ouachita Mountain Systems

The Appalachian mountain system includes the sinuous upland belt that extends for 1,800 miles from northern Alabama northeastward through Maine and the Maritime Provinces of Canada to Newfoundland. It is flanked on the northwest by the Central Interior Region, and on the southeast by gently dipping Mesozoic and **Cenozoic** strata of the Atlantic Coastal Plain. The Appalachian system is the product of complex **plate tectonic** interactions between North America and **oceanic** and **continental plates** that lay to the southeast and south during the Late Proterozoic and the Paleozoic. The system consists of two major belts sometimes referred to as the "sedimentary Appalachians," so called because they consist chiefly of **folded** and **faulted,** but little-metamorphosed, sedimentary rocks, and the "crystalline Appalachians," which consist chiefly of metamorphic and plutonic rocks.

Amidst the Paleozoic rocks of the Appalachians are several fault-bounded basins filled with unmetamorphosed lower Mesozoic red sandstone and shale (unit lMz) interleaved with sheets of mafic intrusive rock (unit lMzm). These basins form a discontinuous series that extends from North Carolina to central Massachusetts, and similar basins are found in Nova Scotia. The basins formed during the initial stages of opening of the present Atlantic Ocean as North America separated from Europe and Africa after formation of the Appalachian mountain system. Less well understood are the Mesozoic granite **plutons** (unit Mzg) in the White Mountains of central New England, which may have formed as a result of movement of the North American plate over a stationary plume of hot material rising from deep in the Earth's mantle.

The Ouachita mountain system is exposed only in a few scattered areas in Arkansas, Oklahoma, and Texas. The rest of the system, which forms the southern border of the North American craton, lies buried beneath younger deposits.

Sedimentary Appalachians

Nonmetamorphosed sedimentary rocks form the northwestern part of the Appalachian mountain system adjacent to the craton. Their boundary with the cratonic cover rocks is at the transition between broad open folds in the cratonic cover to the northwest and the sharply folded and faulted rocks to the south and east. The rocks of the sedimentary Appalachians (units lPz, mg) are chiefly limestone, shale, and sandstone formed from sediments that were deposited during the same interval of time as the sedimentary cover of the eastern parts of the interior lowlands. Many sediments were deposited in seaward-thickening wedges along the edge of the craton, but others accumulated in deep basins that formed during uplift of the mountain system. All of the strata have been folded, and in parts of the belt thick sheets of sedimentary rocks have been displaced many miles northwestward onto the craton along **thrust faults**. The sedimentary Appalachians can be divided into two principal segments, the Valley and Ridge Province and the Taconic Province.

The Valley and Ridge Province is the segment between northeastern Alabama and northeastern Pennsylvania. It is characterized by long, northeast-trending ridges (fig. 3) formed by the upturned edges of resistant sedimentary layers (commonly sandstone) and intervening valleys cut in softer strata (commonly limestone and shale). In the southwestern part of this segment thrust faults are very conspicuous, and some can be traced along the trend of the belt for hundreds of miles. The slices of rocks above and between these faults have been transported tens of miles or more toward the craton. In the northeastern part the rocks are folded into linear **anticlines** and **synclines**, but thrust faults have not been recognized at the surface, although major thrusts may be hidden at depth. Most, and perhaps all, of the deformation in the Valley and Ridge took place during the late Paleozoic.

The Taconic Province is the narrow segment of the sedimentary Appalachians that extends from northeastern Pennsylvania through eastern New

York and western Vermont to the Canadian border. The rocks are chiefly lower Paleozoic strata (unit lPz), mostly sandstone, limestone, **dolomite**, and shale that have been folded and locally carried westward in thin thrust sheets, some of which include Late Proterozoic rocks (units Z, ZPz). In contrast to the Valley and Ridge Province, where most of the folding and faulting took place near the end of the Paleozoic, most of the thrusting and folding in the Taconic Province took place late in the early Paleozoic during the Ordovician.

Crystalline Appalachians

Like the sedimentary Appalachians, the crystalline Appalachians can be divided into two principal segments, a southern segment that extends from northeastern Alabama to eastern Pennsylvania, and a northern segment that includes most of New England.

The southern crystalline Appalachians comprise the broad belt of metamorphic and plutonic rocks that underlie the Blue Ridge and Piedmont Plateau and pass beneath the younger sedimentary rocks of the Atlantic Coastal Plain on the southeast and east. The northwestern part of the belt chiefly includes metamorphosed Late Proterozoic sedimentary and volcanic rocks (units Z and Zv) that overlie Middle Proterozoic gneiss (unit Yn) similar to those exposed in the Adirondacks. In the southwestern part of the belt both the gneiss and the overlying Late Proterozoic rocks have been carried northwestward on thrust faults across the Paleozoic sedimentary rocks of the Valley and Ridge Province. Farther southeast, broad expanses of metamorphosed sedimentary and volcanic rocks of Late Proterozoic or early Paleozoic age (units ZPz, ZPzv, lPz, lPzv) represent sedimentary and volcanic materials that accumulated along the margin of the continent or in and between chains of volcanic islands and were added to North America during plate collisions. Some of the gneiss (unit Yn) in the southeastern part of the belt may at one time have been parts of Africa.

All these rocks occur in slices along major thrust faults that formed during the **docking** of the various **tectonic plates** and plate fragments with the continent. At least three principal **collisional episodes** have been distinguished, each accompanied by intrusion of plutonic rocks, metamorphism, and formation of faults and folds. These include the Taconic episode near the end of the early Paleozoic (accompanied by plutons mapped as unit lPzg), the Acadian episode in the early part of the middle Paleozoic (accompanied by a few plutons mapped as units mPzg and mPzm), and the Alleghenian episode in the late Paleozoic (accompanied by plutons mapped as unit uPzg). The Alleghenian event was the result of the collision of northwestern Africa with North America, and it was during this event that the thrust faults in the Valley and Ridge Province formed.

The New England crystalline Appalachians extend from the valley of the Hudson River and Lake Champlain eastward to the coast. Thus, they encompass most of the New England States. Like the southern crystalline Appalachians, they comprise metamorphosed and strongly folded sedimentary and volcanic rocks intruded by a variety of plutonic rocks of several ages. Along the western edge of the province Middle Proterozoic gneiss (unit Yn) like that in the Adirondack Dome are exposed in a discontinuous series of elongate domes that extends from the Hudson River northward to central Vermont. These basement rocks are overlain by sedimentary and volcanic rocks of Late Proterozoic and early Paleozoic age (Z, lPz), some of which have been carried westward on thrust faults so that they now overlie

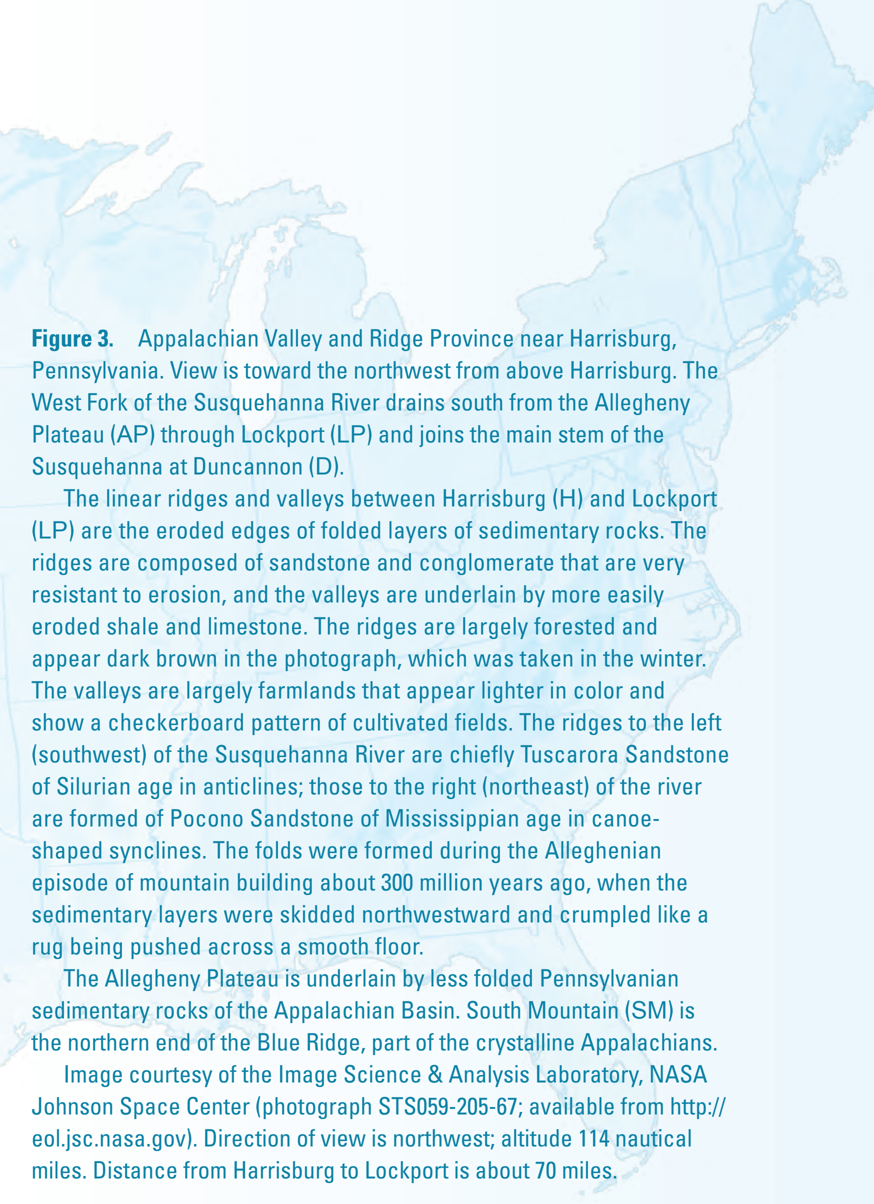
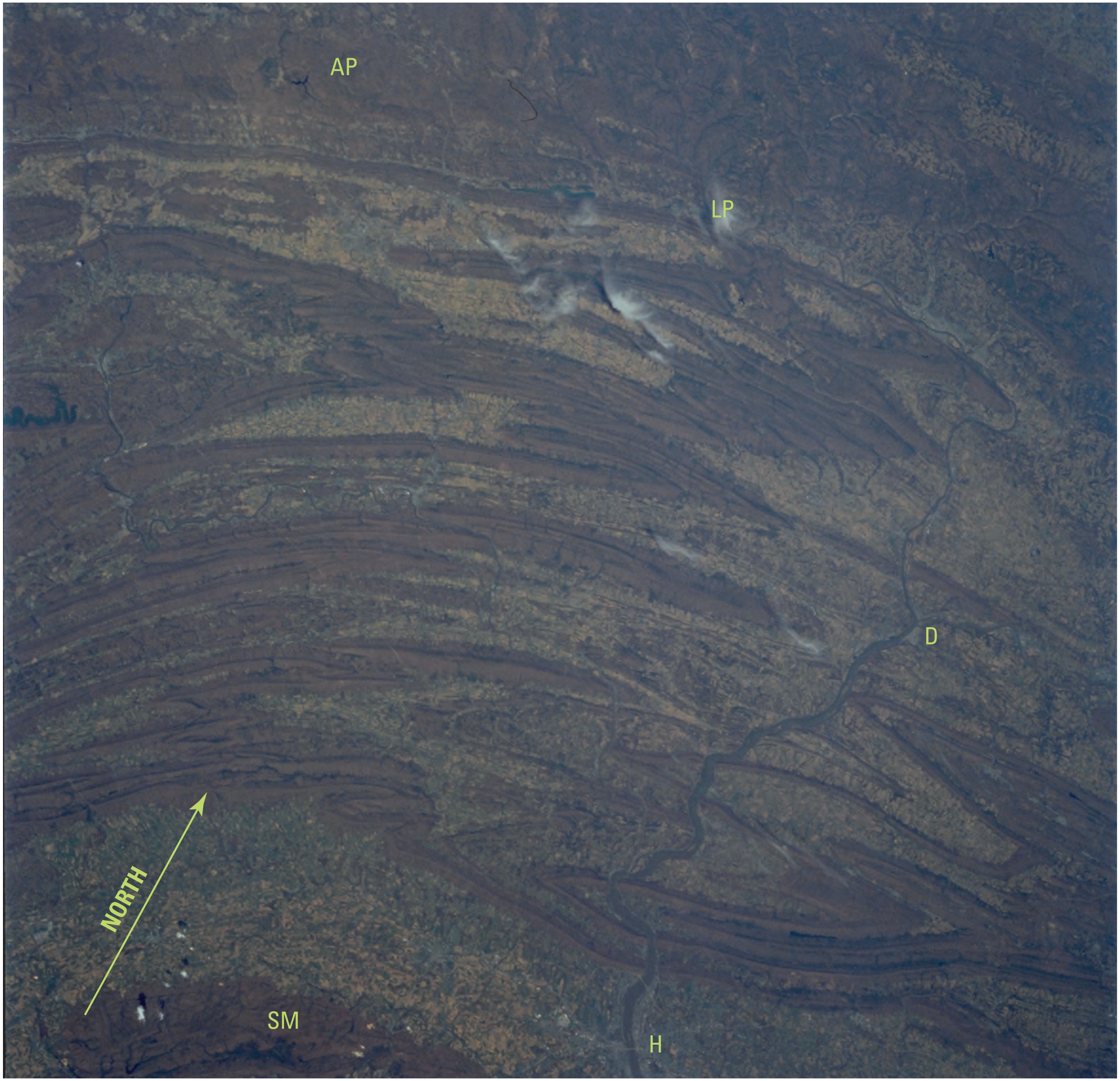


Figure 3. Appalachian Valley and Ridge Province near Harrisburg, Pennsylvania. View is toward the northwest from above Harrisburg. The West Fork of the Susquehanna River drains south from the Allegheny Plateau (AP) through Lockport (LP) and joins the main stem of the Susquehanna at Duncannon (D).

The linear ridges and valleys between Harrisburg (H) and Lockport (LP) are the eroded edges of folded layers of sedimentary rocks. The ridges are composed of sandstone and conglomerate that are very resistant to erosion, and the valleys are underlain by more easily eroded shale and limestone. The ridges are largely forested and appear dark brown in the photograph, which was taken in the winter. The valleys are largely farmlands that appear lighter in color and show a checkerboard pattern of cultivated fields. The ridges to the left (southwest) of the Susquehanna River are chiefly Tuscarora Sandstone of Silurian age in anticlines; those to the right (northeast) of the river are formed of Pocono Sandstone of Mississippian age in canoe-shaped synclines. The folds were formed during the Alleghenian episode of mountain building about 300 million years ago, when the sedimentary layers were skidded northwestward and crumpled like a rug being pushed across a smooth floor.

The Allegheny Plateau is underlain by less folded Pennsylvanian sedimentary rocks of the Appalachian Basin. South Mountain (SM) is the northern end of the Blue Ridge, part of the crystalline Appalachians.

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center (photograph STS059-205-67; available from http://eol.jsc.nasa.gov). Direction of view is northwest; altitude 114 nautical miles. Distance from Harrisburg to Lockport is about 70 miles.


AP
LP
D
H
SM
NORTH

unmetamorphosed lower Paleozoic strata. This belt of Middle Proterozoic gneiss and its cover rocks were apparently part of North America at the beginning of the Paleozoic; most of the rocks to the east originated in or between tectonic plates or plate fragments that were added to the continent during the Paleozoic.

The same episodes of plate collision accompanied by metamorphism and intrusion of plutonic rocks that affected the southern crystalline Appalachians are recognized in the New England crystalline Appalachians. During the Taconic episode (near the end of the early Paleozoic) fragments of tectonic plates that included the lower Paleozoic rocks (unit lPz) in New Hampshire and southwestern Maine were added to the margin of the continent. Granite plutons (unit lPzg) were emplaced, and the rocks were folded, faulted, and metamorphosed. Following the Taconic episode, the earlier folds and faults were truncated by erosion and a thick and widespread blanket of middle Paleozoic sandstone, conglomerate, shale, and limestone (unit mPz) accumulated across the older rocks. These strata have no counterparts in the southern crystalline Appalachians. The middle Paleozoic Acadian episode was apparently related to docking of plate fragments that now make up much of southeastern Maine, eastern New Hampshire, and central Massachusetts. It also resulted in widespread folding and metamorphism of the middle Paleozoic cover rocks (unit mPz) to the northwest and in the emplacement of widespread plutonic rocks (units mPzg and mPzm) in New Hampshire and central Maine. The Alleghenian episode (near the end of the Paleozoic) included the accretion of plate fragments that now occupy extreme eastern Maine (units mPzv and mPzm) and southeastern Massachusetts (units Zg, uPz) to the edge of the continent and the intrusion of granite plutons (unit uPzg).

Ouachita Mountain System

The Ouachita mountain system is a belt of sedimentary rocks deformed during the late Paleozoic. This belt (fig. 4) is similar to the Valley and Ridge Province of the Appalachians. The Ouachita system extends westward from the southern end of the Appalachian system in central Alabama through Mississippi and Arkansas, into western Texas. Although the system is almost 1,300 miles long, it is exposed only in the Ouachita Mountains of western Arkansas and eastern Oklahoma and in the Marathon Uplift in southwestern Texas. The remaining 90 percent of the system is buried beneath younger deposits and is known only from deep drilling and from **geophysical studies**. Like the Valley and Ridge Province, the Ouachita system consists of Paleozoic rocks that have been folded and carried toward the continental interior in thrust sheets, overriding the Paleozoic sedimentary rocks, chiefly sandstone, shale, and limestone that blanket the southern part of the craton. In contrast to the sedimentary rocks of the cratonic cover, which were mostly deposited in shallow seas, the rocks carried northward in the thrust sheets are chiefly shale, siltstone, sandstone, **chert**, and **novaculite** deposited in much deeper water along the edge of the continent. Most of the deep-water sedimentary rocks are of essentially the same age as the shallow-water cratonic cover rocks to the north and thus are also shown on the map as units lPz and mPz. The upper Paleozoic rocks (unit uPz) consist of sandstone, shale, and some conglomerate deposited during various phases of movement of the thrust sheets during the **Mississippian, Pennsylvanian**, and Early **Permian**. Some of these rocks were carried northward in the thrust sheets, and some accumulated in basins along the edge of the craton north of the main belt of thrusting and folding.

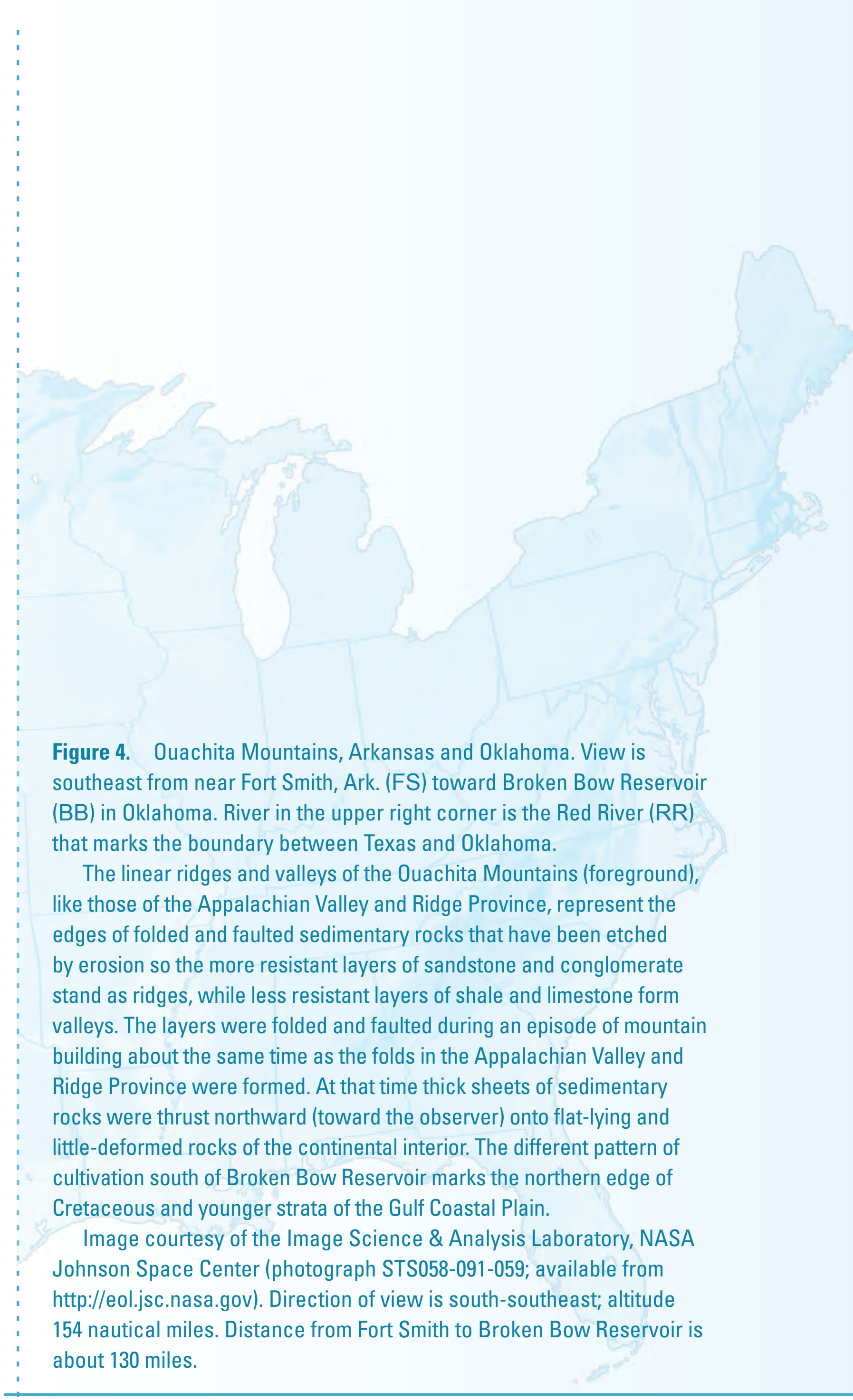
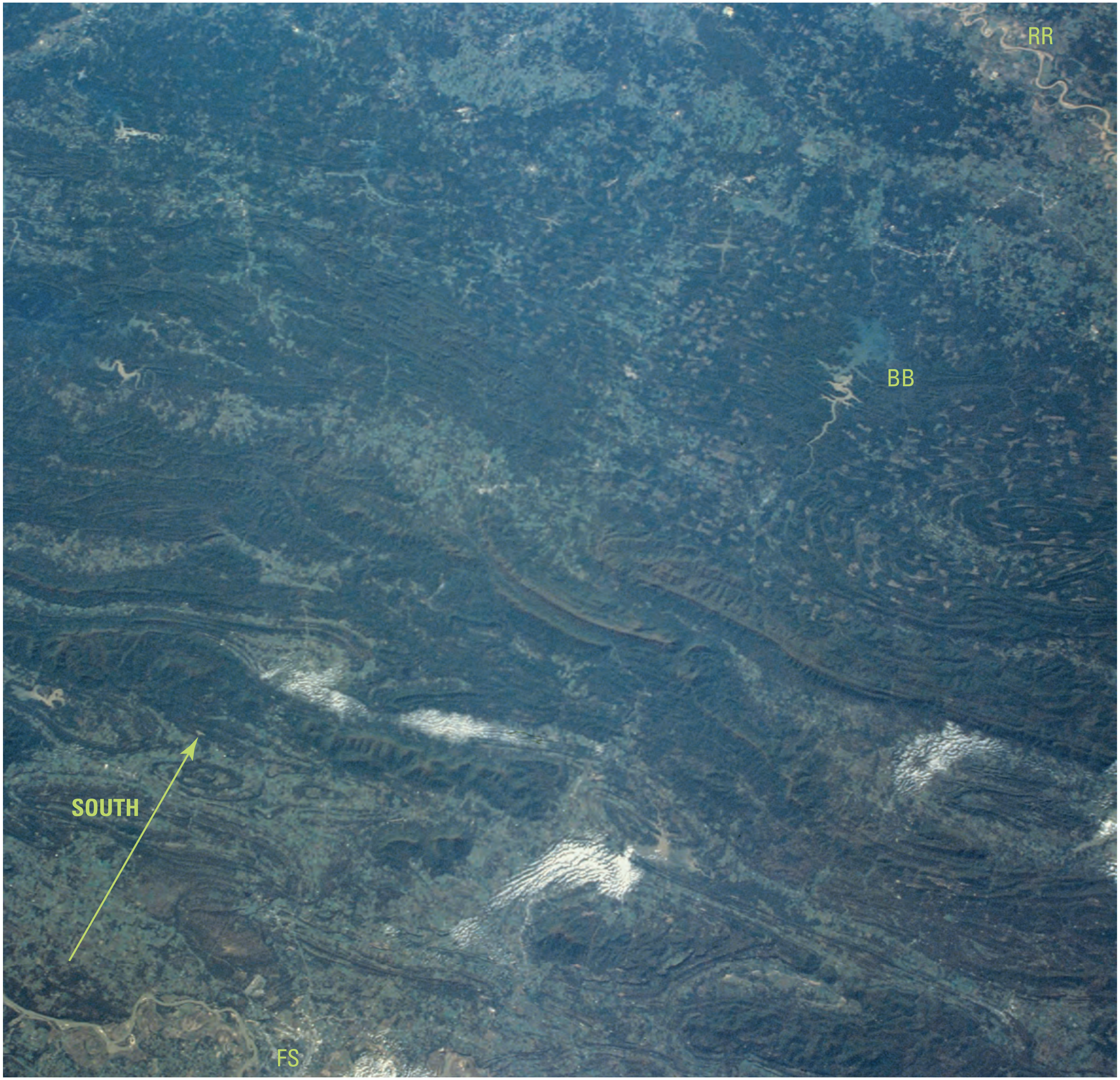


Figure 4. Ouachita Mountains, Arkansas and Oklahoma. View is southeast from near Fort Smith, Ark. (FS) toward Broken Bow Reservoir (BB) in Oklahoma. River in the upper right corner is the Red River (RR) that marks the boundary between Texas and Oklahoma.

The linear ridges and valleys of the Ouachita Mountains (foreground), like those of the Appalachian Valley and Ridge Province, represent the edges of folded and faulted sedimentary rocks that have been etched by erosion so the more resistant layers of sandstone and conglomerate stand as ridges, while less resistant layers of shale and limestone form valleys. The layers were folded and faulted during an episode of mountain building about the same time as the folds in the Appalachian Valley and Ridge Province were formed. At that time thick sheets of sedimentary rocks were thrust northward (toward the observer) onto flat-lying and little-deformed rocks of the continental interior. The different pattern of cultivation south of Broken Bow Reservoir marks the northern edge of Cretaceous and younger strata of the Gulf Coastal Plain.

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center (photograph STS058-091-059; available from http://eol.jsc.nasa.gov). Direction of view is south-southeast; altitude 154 nautical miles. Distance from Fort Smith to Broken Bow Reservoir is about 130 miles.


RR
BB
SOUTH
FS

Coastal Plain Province

The southern and southeastern margins of the conterminous United States are covered by wide coastal plains composed of sediments that were deposited along the passive edges of the continent as North America separated from Africa to form the present Atlantic Ocean and from northern South America to form the Gulf of Mexico. For descriptive purposes it is convenient to divide the province into three segments: the Atlantic Coastal Plain, the Florida Peninsula, and the Gulf Coastal Plain.

Atlantic Coastal Plain

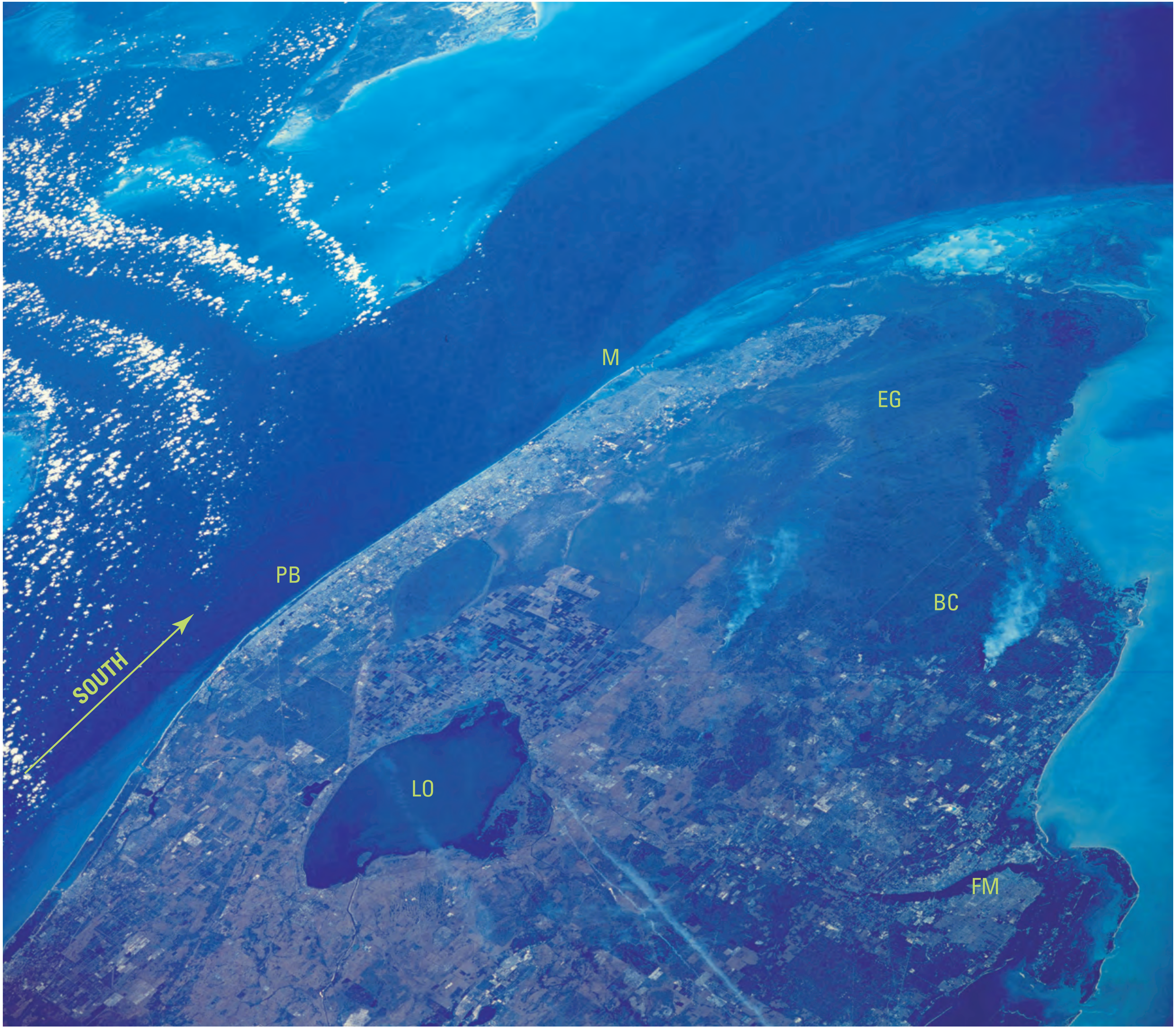
The Atlantic Coastal Plain extends from Long Island, N.Y., southward to northern Florida, widening from a few miles in northern New Jersey to more than 100 miles in South Carolina and Georgia. It is underlain by a seaward-thickening wedge of Cretaceous, Tertiary, and Quaternary sediments that overlie metamorphic and igneous rocks of the crystalline Appalachians. The wedge thickens southeastward from its inner edge to more than 6,500 feet along the coast and extends southeastward beneath the continental shelf, where it locally reaches a maximum thickness of 33,000 feet. The continental separation that led to the accumulation of the coastal plain sediments began during the early Mesozoic, as indicated by the fault-bounded basins filled with **Triassic** and **Jurassic** sedimentary and igneous rocks in the crystalline Appalachians. The oldest rocks exposed on the Atlantic Coastal Plain are Cretaceous, although drilling and geophysical studies show that lower Mesozoic rocks are present at depth along the coast and beneath the continental shelf. Most of the exposed Cretaceous (unit K) and Tertiary (units pgT and nT) sedimentary rocks were formed from sand, silt, and clay deposited in shallow waters on the continental shelf or near deltas where rivers emptied into the sea. Some of these rocks were formed from sand, gravel, and clay deposited on land during low stands of sea level. The Quaternary deposits include river-deposited sand and gravel, and sand deposited on beaches and in sand dunes, as well as organic materials laid down in coastal swamps. On Long Island, the Quaternary deposits are chiefly **till** in glacial **moraines**, and in New Jersey they include sand and gravel carried by rivers flowing off the melting glacial ice.

Florida Peninsula

The Florida Peninsula (fig. 5) is underlain by nearly flat-lying sedimentary rocks of Cretaceous and Tertiary age that locally attain a thickness of more than 20,000 feet. Unlike the rocks of the Atlantic Coastal Plain, which overlie metamorphic and igneous rocks of the crystalline Appalachians, those in Florida overlie little-metamorphosed Paleozoic sedimentary rocks and Precambrian igneous and metamorphic rocks that may represent a part of Africa that remained attached to North America during the opening of the modern Atlantic Ocean. The oldest rocks exposed in the peninsula are chiefly limestone, **evaporite**, shale, and sandstone of early Tertiary age (unit pgT). These rocks are largely mantled by upper Tertiary rocks (unit nT), chiefly sandstone, shale, and

Figure 5. South Florida and the Everglades. View southeast from over west coast north of Fort Myers (FM) toward Palm Beach (PB) and Miami (M). The Florida Peninsula is underlain by thousands of feet of flat-lying sedimentary rocks, chiefly limestone, deposited during Cretaceous, Tertiary, and Quaternary time. The present landscape of southern Florida is the result of variations in sea level during the Pleistocene Ice Ages. As glaciers grew, water was withdrawn from the oceans and sea level fell, at times by several hundred feet. During interglacial intervals, glaciers melted and water returned to the oceans, raising sea level and flooding southern Florida. During the low stands of sea level, limestone was dissolved and eroded to form caves and sinkholes; during high stands, limestone was deposited and beaches and dunes were created. As the most recent ice age ended, about 12,000 years ago, sea level began to rise and continues to rise today. The rising sea level impeded drainage of fresh water and led to the accumulation of thick layers of peat beginning about 5,000 years ago. These peat deposits form the Everglades (EG) and the Big Cyprus (BC) Swamp. Lake Okeechobee (LO) occupies a solution depression in the limestone. Natural drainage is southward from central Florida through Lake Okeechobee into the Everglades. Construction of levees, dikes, and drainage canals has disrupted the natural drainage in the region with drastic effects on the ecosystems. Diagonal streak in lower part of the photograph is an airplane contrail; plumes of smoke from burning vegetation are visible in the right part of the picture.

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center; (photograph STS51C-143-0032; available from http://eol.jsc.nasa.gov). Direction of view is southeast; altitude not given. Distance from Fort Myers to Palm Beach is about 115 miles.


M
EG
PB
BC
SOUTH
LO
FM

limestone formed from sediments deposited in shallow seas on the continental shelf, and by Quaternary deposits (unit Q), chiefly sand deposited along beaches and in sand dunes, and by mud deposited in coastal swamps.

Gulf Coastal Plain

The Gulf Coastal Plain extends from the panhandle of Florida westward into southern Texas and then southward into central Mexico. It ranges in width from about 200 miles in Alabama and Mississippi to as much as 300 miles in Texas, but a major northward projection of the coastal plain, the Mississippi Embayment, extends nearly 500 miles northward up the Mississippi River to its junction with the Ohio. Like the Atlantic Coastal Plain, the Gulf Coastal Plain consists of a seaward-thickening wedge of Mesozoic, Tertiary, and Quaternary rocks formed from sediments that were deposited along the subsiding margin of the continent as North America separated from adjacent tectonic plates during the early Mesozoic.

The oldest rocks exposed at the surface in the Gulf Coastal Plain are Cretaceous. In Texas these rocks are chiefly limestone, shale, and sandstone of Early Cretaceous age, older than any known on the Atlantic Coastal Plain. East of the Mississippi, the Cretaceous rocks are all Upper Cretaceous, like those of the Atlantic Coastal Plain, but they include chalk and limestone. Most of the Cretaceous sediments were deposited on shallow continental shelves, along beaches, or in deltas where rivers entered the sea.

The exposed Tertiary rocks (units pgT, nT) are chiefly shale, sandstone, and limestone that originated as sediments deposited in shallow seas, in river **deltas**, and on land in coastal plains. The Quaternary rocks include beach, coastal swamp, and dune deposits, in addition to sand, silt, and clay deposited in river deltas.

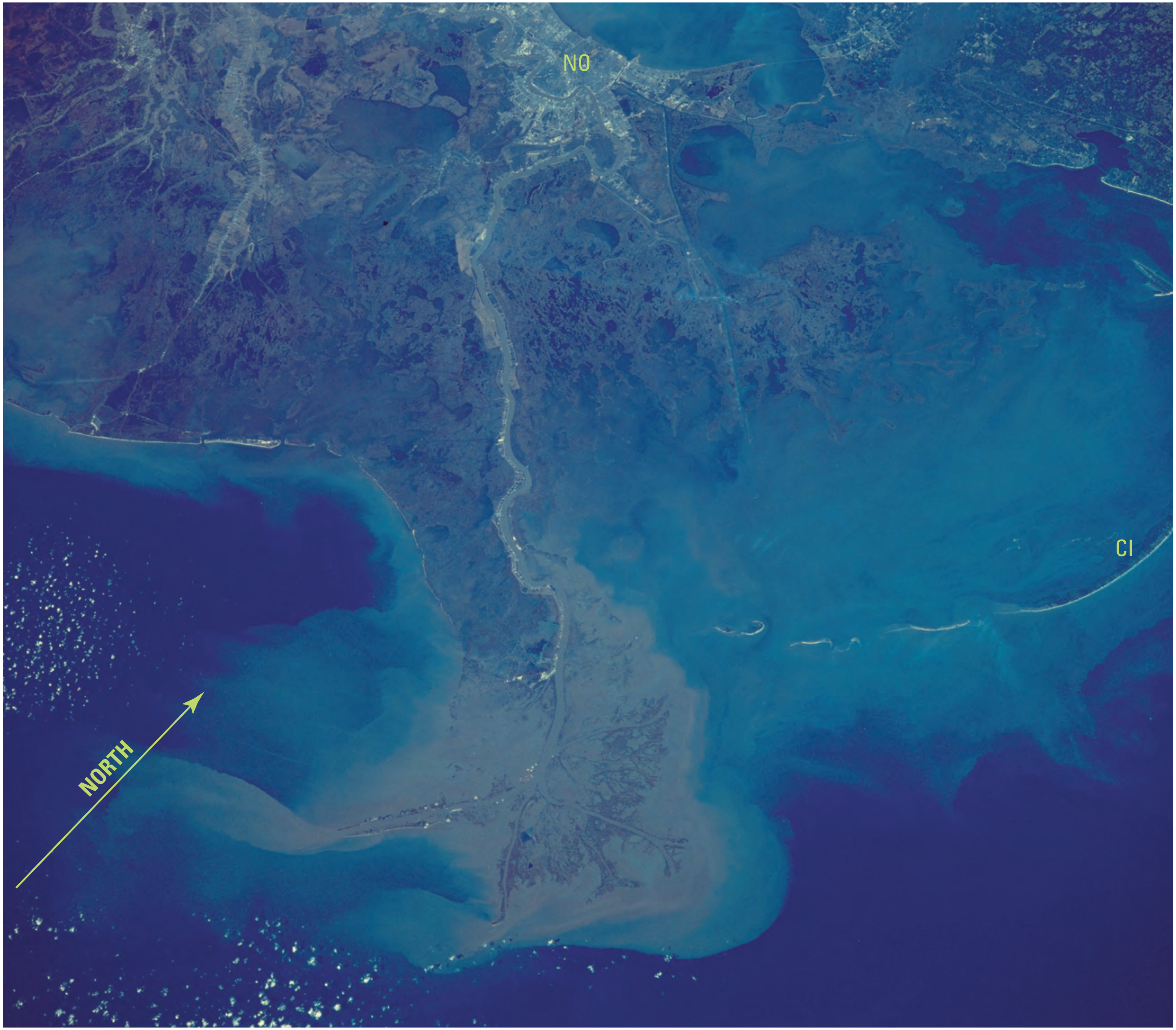
In addition to its greater geographic extent and in the much greater proportion of limestone and chalk in the Cretaceous and Tertiary strata, the Gulf Coastal Plain differs from the Atlantic Coastal Plain in two other important aspects. First, the older Mesozoic strata, which are not exposed but which underlie much of the southern part of the coastal plain, contain a thick layer of salt, which flows readily under pressure when deeply buried by younger sediments. Second, the Mississippi River system, which drains much of the central part of the continent, has delivered vast amounts of soft mud, clay, and sand to the Mississippi delta and to the Gulf of Mexico during the Tertiary and Quaternary. These deposits reach a thickness of as much as 8,000 feet on the delta at the river mouth (fig. 6) and as much as 16,000 feet beneath the floor of the Gulf. As the salt flows under the weight of these deposits, some of it moves upward in pipelike bodies called salt domes, some of which penetrate all the way to the land surface or to the sea floor. The upwarped strata along the margins of these domes form traps for petroleum and natural gas, and the domes that approach the surface are commonly mined for salt. Flowage of the salt plus downslope movement of the soft Tertiary and Quaternary sediments toward the deep Gulf of Mexico Basin has produced a complex series of faults in the coastal plain deposits, some of which are still moving. Some of these **growth faults** are shown on the map.

Figure 6. The Mississippi Delta and New Orleans, Louisiana. View northwest from over the mouth of the Mississippi River toward New Orleans (NO). The Mississippi River drains more than one-third of the conterminous United States. Each year it carries about 125 cubic miles of water to the Gulf of Mexico. More than two-thirds of this flow enters the Gulf down the main channel below New Orleans, shown in this photograph. The remainder of the flow enters the Gulf through the Atchafalaya, a branch of the Mississippi that enters the Gulf about 115 miles to the west. The river carries more than 180 million tons of silt, clay, and sand into the Gulf each year, exclusive of the material rolled along the bottom or carried in solution. The sediments are as much as 8,000 feet thick near the river mouth and as much as 16,000 feet farther south beneath the Gulf of Mexico. Slumping and slow creep of the soft sediments causes the widespread faults shown on the geologic map and continuing subsidence of the delta.

The distinct color change in the lower delta reflects the difference between vegetation growing in freshwater swamps near the river mouth and that growing in salt marshes farther inland, where the supply of freshwater has been cut off as the delta advances. The Chandeleur Islands (CI) are barrier islands built by reworking of the delta sediments by waves and currents.

This photograph was taken in January 1985, long before the devastation caused by hurricane Katrina.

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center; (photograph STS51C-143-0027; available from http://eol.jsc.nasa.gov). Direction of view is northwest; altitude not given. Distance from tip of the delta to New Orleans about 80 miles.


NO
CI
NORTH

Cordilleran Mountain System

The mountain ranges, basins, and plateaus that lie between the Central Interior Region and the Pacific Coast are part of the Cordilleran mountain system, a belt of highlands that extends for almost 4,000 miles along the western margin of North America from Alaska through parts of Canada, the conterminous United States, Mexico, and Central America. The widest part of the Cordilleran mountain system is in the western conterminous United States, where it reaches a width of about 1,000 miles between Denver and San Francisco. Just as the Appalachian and Ouachita mountain systems are products of plate interactions along the eastern and southern margins of the North American craton largely during the Paleozoic, the Cordilleran mountain system resulted from plate interactions along the western margin of the craton largely (but not entirely) during the Mesozoic and Cenozoic. Sizable parts of the mountain belt consist of material from oceanic plates that was shoved against, beneath, or onto the western edge of North America as oceanic plates to the west were **subducted** beneath or slid past the western continental margin. As a result of these processes an area of almost 400,000 square miles (almost one and one-half times the size of Texas) was added to the western edge of the continent in the conterminous United States alone.

For purposes of description, the Cordilleran mountain system is divided into a number of subregions, each characterized by a different geologic history, but many of the boundaries between these subregions are gradational and the lines drawn between them are somewhat arbitrary.

Laramide Rocky Mountains

The Laramide Rocky Mountains are a series of asymmetric mountain ranges cored (fig. 7) by Precambrian basement rocks and their cover of Paleozoic and Mesozoic sedimentary rocks that were originally part of the craton. These ranges are generally bounded by sharp flexures in the sedimentary cover or by moderately to steeply inclined faults that slope beneath the uplifted block. The ranges are separated by basins filled with debris shed during and after the uplift, which took place during a relatively short interval in latest Cretaceous and earliest Tertiary time. This episode of uplift is called the **Laramide orogeny**. It takes its name from the Laramie Formation, a deposit of sandstone and shale shed from the uplifts into neighboring basins in Colorado and Wyoming. For descriptive purposes the Laramide Rocky Mountains are divided into two parts, the northern Laramide Rocky Mountains in Montana, Wyoming, and northernmost Utah, and the southern Laramide Rocky Mountains in Colorado and New Mexico.

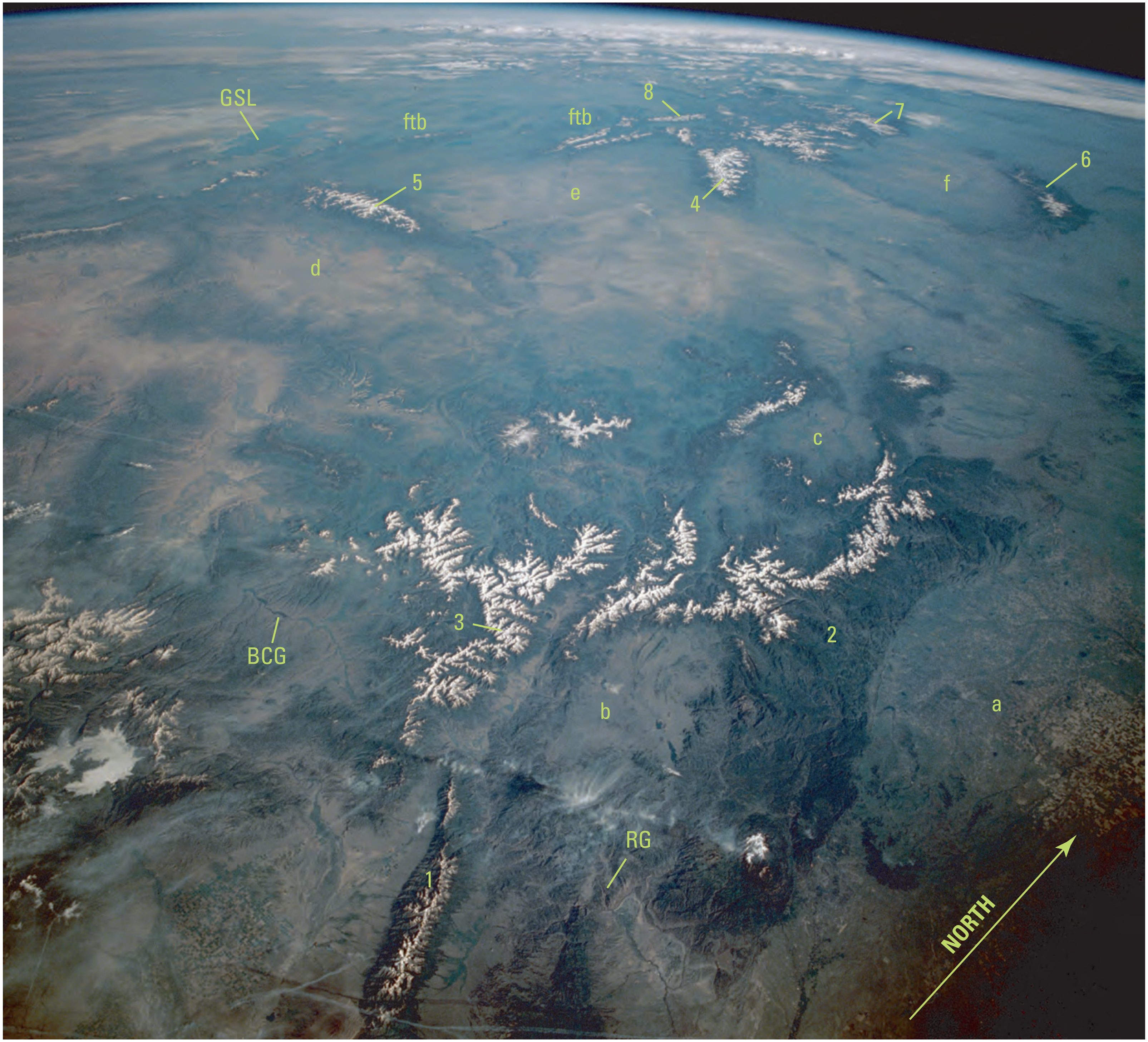
The principal features of the northern Laramide Rocky Mountains are the elongate fault-bounded basement uplifts and the intermontane basins. The uplifts are indicated by circled numbers on the index map (fig. 2), the basins by circled letters.

The uplifts include the northwest-trending Bighorn Uplift (1) and other uplifts in southwestern Montana, the Beartooth (2), and Wind River (3) uplifts in northwestern Wyoming, the northwest-trending Laramie Uplift (4) in south-central Wyoming, and the east-west-trending Uinta Uplift (5) in Utah. The basement rocks in all of these except the

Figure 7. The Laramide Rocky Mountains. View northwest from over Pueblo, Colorado. Most of the ranges in this view represent the cores of uplifts that rose between 70 and 45 million years ago during the Laramide period of mountain building. Erosion during and after the uplift stripped away the softer sedimentary rocks, exposing the harder sedimentary strata and Precambrian basement rocks that form the present mountain ranges. At the same time the surrounding basins were filled with the materials eroded from the uplifts. The basement rocks beneath the basins lie tens of thousands of feet below the same rocks exposed in the cores of the uplifts. During later uplift of the entire region erosion cut deep canyons, such as the Royal Gorge and the Black Canyon of the Gunnison. The linear valley west of the Sangre de Cristo Range and east of the Sawatch Range is part of the Rio Grande Rift.

Laramide uplifts (identified by numbers) include Sangre de Cristo Range (1), Front Range (2), Sawatch Range (3), Wind River Range (4), Uinta Mountains (5), Bighorn Mountains (6), Beartooth Mountains (7), and Teton Range (8). Laramide basins (identified by letters) include Denver Basin (a), South Park (b), North Park (c), Uinta Basin (d), Green River Basin (e), Bighorn Basin (f). Other features include Great Salt Lake (GSL), Black Canyon of the Gunnison (BCG), Royal Gorge (RG), and various ranges in the Fold and Thrust Belt (ftb).

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center; (photograph STS040-604-011; available from http://eol.jsc.nasa.gov). Direction of view is northwest; altitude 155 nautical miles. Distance from north end of the Sange de Cristo Range to Great Salt Lake is about 400 miles.


GSL
ftb
ftb
8
7
5
e
4
f
6
d
c
3
BCG
2
b
a
RG
1
NORTH

Uinta Uplift are granite and gneiss of Archean age (units Ag, An). The core of the Uinta Uplift comprises little-metamorphosed Proterozoic sandstone (unit Ᵽ) that apparently accumulated in a local downwarp in the craton.

The basins include the Bighorn Basin (A) in northwestern Wyoming, the Wind River Basin (B) in central Wyoming, and the Green River (C) and Red Desert Basins (D) in south-central Wyoming. All these basins are floored by Paleogene rocks (unit pgT) composed of materials eroded from the uplifts and deposited during the late stages of Laramide uplift and after the uplift ceased. The Archean basement rocks (units A, An, Ag) beneath the deepest basins lie as much as 20,000 feet below sea level; the same rocks in some of the adjacent uplifts stand at elevations of more than 13,000 feet above sea level. Thus, the relative change in elevation of the surface of the basement rocks during the Laramide orogeny was as much a 6 miles. Erosion of the Laramide uplifts also furnished material to the Powder River and Williston Basins to the east.

The southern Laramide Rocky Mountains differ from the northern Laramide Rocky Mountains in that most of the uplifts and basins trend nearly north-south and that the basement rocks exposed in the cores of the uplifts are all of Proterozoic age. The basement rocks are schist, gneiss, and granitic rocks (units Xn, Xg, Yg) that range in age from 1.8 to 1.0 billion years and thus are considerably younger than those in uplifts to the north. The uplifts in the southern Laramide Rocky Mountains include the Front Range (6) and Park Range–Sierra Madre (7) in northern Colorado and southernmost Wyoming, the Sawatch (8) in central Colorado, the Sangre de Cristo (9) in southern Colorado and northern New Mexico, and the Sandia and San Andreas (not distinguished on map) in central and southern New Mexico.

Intermontane basins include North Park and South Park in Colorado, which are too small to be shown on the map. The Laramide uplifts also furnished material to the Denver Basin to the east. If the basins in the southern Laramide Rocky Mountains were ever as extensive as those in the northern Laramide Rocky Mountains, much of the basin fill has since been removed by erosion.

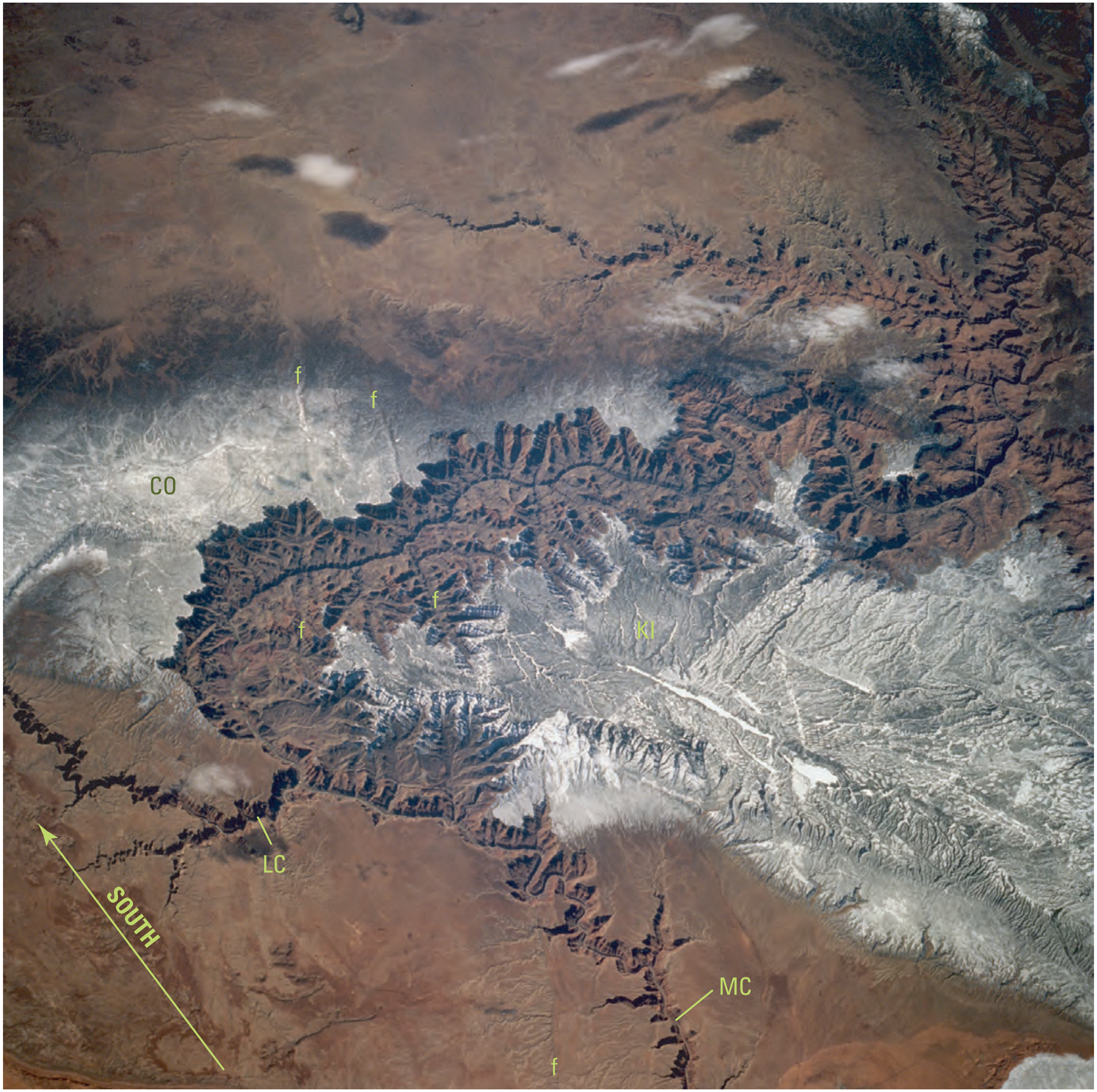
Colorado Plateau

The Colorado Plateau is an irregular, but roughly equidimensional, region of relatively flat-lying Paleozoic and Mesozoic sedimentary rocks that lies west of the southern Laramide Rocky Mountains and the Rio Grande Rift, discussed in a later section. The plateau extends from northeastern Utah southward for nearly 450 miles into central Arizona, and from the Rio Grande Rift in southern Colorado and northern New Mexico for almost 400 miles westward through northern Arizona. It is capped largely by upper Paleozoic, lower Mesozoic, and Cretaceous rocks. Lower Paleozoic strata and the basement rocks that underlie them are exposed only in the Grand Canyon in northwestern Arizona (fig. 8) and along the southern margin of the plateau in central Arizona. The basement rocks are all of Proterozoic age and are closely related to the Proterozoic rocks exposed in the Laramide uplifts in the southern Laramide Rocky Mountains. The Colorado Plateau is an isolated piece of the craton separated from the Interior Lowlands by uplift of the Laramide Rocky Mountains. The plateau itself has also been uplifted, so that the surface of the basement rocks beneath it stands 2,500 feet or more above the

Figure 8. The Grand Canyon, Arizona. The Grand Canyon, more than a mile deep and 277 miles long, was carved by the Colorado River through flat-lying sedimentary rocks of the Colorado Plateau largely during the last 5 million years. The river enters the Grand Canyon through Marble Canyon (MC). The Little Colorado River (LC) flows north through a smaller canyon to join the Colorado as shown in the lower left part of the photograph. The snow-covered Coconino Plateau (CO) and Kaibab Plateau (KI) and the surrounding flat desert are capped by siltstone, sandstone, and limestone of Permian age. Older Paleozoic strata are exposed in the canyon walls, where resistant layers of sandstone and limestone form jagged towering cliffs, and layers of less resistant shale form smoother and gentler slopes. Downstream from the mouth of the Little Colorado gently tilted Late Proterozoic sedimentary rocks and lava about 1.1 billion years old are exposed at river level. Finally, in the deepest parts of the canyon, the river has cut into metamorphic rocks and granite more than 1.7 billion years old. The straight southwest-trending linear features that cross the canyon as shown in the left center of the photograph and extend onto the surface of the Coconino Plateau mark faults along which the sedimentary layers have been offset. Some of the faults are marked (f).

The distance across the narrowest part of the canyon from the snow-covered part of the Coconino Plateau to the snow-covered part of the Kaibab Plateau is about 8 miles.

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center; (photograph; STS060-83-005 available from http://eol.jsc.nasa.gov). Direction of view is southwest; altitude 192 nautical miles. The horizontal distance across the center of the area shown is about 60 miles.


f
f
CO
f
f
KI
LC
SOUTH
MC
f

basement surface in the Interior Lowlands and the top of the plateau stands 6,500–8,000 feet above sea level.

Deep basins (circled letters on the map) filled with thousands of feet of **Paleogene** rocks (unit pgT) fringe the plateau on the north and east. These include the Uinta Basin (A) in northeastern Utah, the Piceance Basin (B) in northwestern Colorado, and the San Juan Basin (C) in southwestern Colorado and northwestern New Mexico. The basin-filling sediments are chiefly debris shed from the flanking Laramide uplifts but include some deposits that accumulated in large lakes that occupied parts of the Uinta and Piceance Basins.

In the central part of the plateau the flat-lying sedimentary rocks were intruded by igneous rocks (unit pgTi) that were emplaced very late in the Paleogene. These intrusive rocks form tabular and mushroom-shaped bodies that bowed up the sedimentary strata above them and were eventually exposed by erosion so that they stand as isolated groups of mountains.

Along the southern edge of the plateau are several young volcanic fields in which lavas, chiefly basalt and related rocks (units nTv, Qv) were erupted from groups of central volcanoes. Among these is the San Francisco volcanic field (1)**,** whose prominent volcanic peaks rise above Flagstaff, Ariz.

Rocky Mountain Fold and Thrust Belt

In westernmost Wyoming, eastern Idaho, and western Montana the Rocky Mountain fold and thrust belt is quite different geologically from the Laramide Rocky Mountains. Instead of the broad fault-bounded Laramide uplifts in which basement rocks are exposed, the mountain ranges in the fold and thrust belt consist largely of sedimentary rocks that originally were tens of miles or more west of their present positions. These strata now lie in a stacked series of thin sheets that have been folded and carried eastward toward the craton along thrust faults, mostly during the Mesozoic. This episode of folding and thrust faulting is often referred to as the “Sevier orogeny.” The Sevier started during the early Mesozoic, before the Laramide orogeny, and ended near the end of the Cretaceous, while the Laramide orogeny was still in progress. Although they overlap in time, the geological structures produced by these two orogenies are quite different.

The Rocky Mountain fold and thrust belt extends northward from the conterminous United States through western Canada and into the Brooks Range in northern Alaska. The same structures also extend southward through Utah, Nevada, and Arizona, but there they are sundered by later faults of the Basin and Range Province (described below) to such a degree that they cannot be shown on a map of this scale. From eastern Arizona the belt continues southeastward through eastern Mexico into northern Central America. The geological structure of the fold and thrust belt is very similar to that of the Valley and Ridge Province of the Appalachians, although both the age and the direction of transport on the thrusts are different (but in both cases the transport direction is away from the continental margin and toward the craton).

The segment of the fold and thrust belt in the conterminous United States can conveniently be divided into two segments, one in Idaho and Montana and one in western Wyoming.

In the Idaho-Montana segment of the fold and thrust belt the rocks in the thrust sheets are chiefly sandstone, **argillite**, and thin beds of dolomite of Middle Proterozoic age (unit Y). These strata were deposited in an extensive basin on what was then the western edge of the continent. Paleozoic and Mesozoic rocks appear in the thrust sheets in this segment only along its northeastern and southeastern margins. In western Montana the continuity of the north-northwest-trending thrust faults is broken by a series of northwest-trending faults called the Lewis and Clark zone. The northeast side of each of these faults has moved northwestward with respect to the southwest side, displacing the structures of the fold and thrust belt.

South of the Lewis and Clark zone, large bodies of Cretaceous and Paleogene granitic rocks (units Kg, pgTg) intruded the rocks of the fold and thrust belt, some during, but most after, movement on the thrust faults. The largest of these bodies are the Idaho **batholith** and the Boulder batholith. In a broad zone surrounding the Idaho batholith the Middle Proterozoic sedimentary rocks (unit Y) were metamorphosed to gneiss (unit Yn).

The Wyoming segment of the fold and thrust belt lies chiefly in western Wyoming but extends into southeastern Idaho and north central Utah. The sedimentary rocks in the thrust sheets in this segment range in age from Late Proterozoic through Late Cretaceous, but because of the scale of the map they have been grouped simply as Paleozoic and Mesozoic (units Pz and Mz). No large bodies of granitic rocks like those in Montana and Idaho have intruded this segment of the fold and thrust belt.

Basin and Range Province

West and south of the Colorado Plateau is a broad region characterized by linear mountain ranges separated by sediment-filled basins (fig. 9). This region, known as the Basin and Range Province, extends north into Idaho and encompasses a large part of northwestern Utah, most of Nevada, and southeastern California, and extends eastward through southern Arizona and New Mexico, and southward into northern Mexico. In Utah and most of Nevada the trends of the ranges are nearly north-south, but in northwestern Nevada trends are northeasterly and in Arizona and New Mexico many ranges trend northwest. Rocks exposed in the ranges include Late Proterozoic, Paleozoic, and Mesozoic sedimentary rocks (units Z, Pz, Mz) and Tertiary volcanic rocks (units pgTv, nTv). The materials filling the basins are chiefly fan-shaped deposits of gravel and sand eroded from the nearby ranges but include sediments deposited in extensive lakes that occupied the basins during the ice ages, when the climate was wetter. Much of the province in Utah and Nevada is part of the Great Basin, an area from which no streams escape to the sea.

Unlike most mountain ranges, the mountains of the Basin and Range Province are produced by pulling apart of the Earth's crust, rather than by compression of the crust as in the fold and thrust belt. The ranges are bounded by faults on one or both flanks, along which the mountain blocks have been raised relative to the intervening basin blocks. The faulting that produced the Basin and Range Province began in the late Paleogene, but most of the movement took place during the Neogene. Some of the faults are still moving today, as evidenced by new fault scarps formed during earthquakes in the past few decades. The total extension of the crust across the Basin and Range is estimated to have been 100 miles or more.

The fold and thrust belt originally extended through much of the Basin and Range Province, but the thrust faults have been cut apart by the younger and more steeply inclined basin and range faults so that the older structures are difficult to decipher. The Basin and Range Province in the conterminous United States can be divided into two subprovinces: the northern, or Great Basin, subprovince, and the southern, or Sonoran, subprovince.

The boundary between the Basin and Range Province and the Colorado Plateau is delineated by a number of volcanic centers that were active during and after the extensional faulting. These centers erupted large volumes of dark lava and widespread blankets of light-colored volcanic ash.

The Great Basin subprovince includes the parts of the Basin and Range Province in Utah and Nevada and a small segment in central Idaho north of the Snake River Plain. In Utah and eastern Nevada the rocks exposed in the ranges are Late Proterozoic and Paleozoic (units Z, Pz) and resemble those in the adjacent Wyoming segment of the fold and thrust belt. However, in central Nevada the Paleozoic rocks (unit Pz) in the ranges include chert, shale, and basalt that were deposited in much deeper water and were thrust eastward onto the edge of the continental shelf during the late Paleozoic. In western Nevada the ranges also include lower Mesozoic sandstone, shale, and volcanic rocks that were thrust onto the edge of the continent near the end of the early Mesozoic.

Faults in this part of the Basin and Range Province are currently more active than those elsewhere in the province. Continuing fault movement and the desert climate prevent drainage from the Great Basin from reaching the sea.

The Sonoran subprovince comprises the parts of the Basin and Range Province in southeastern California, Arizona, and New Mexico. In this region the ranges generally trend north-northwest. The uplifted blocks include Proterozoic rocks (units Xn, Xg, Yg) similar to those in Colorado and New Mexico; these rocks presumably form the basement beneath the Colorado Plateau. They also include Paleozoic rocks like those of the Colorado Plateau in thrust sheets that were emplaced during the Sevier orogeny. In addition, in southern Arizona they locally include lower Mesozoic sedimentary and volcanic rocks that accumulated in and between chains of volcanoes along the margin of the continent. Movement on the range-bounding faults in the southern Basin and Range terminated by about 5 million years ago, so that sand and gravel eroded from the ranges has blanketed the faults—thus very few of them are shown on the map.

Rio Grande Rift

The Rio Grande Rift in Colorado (fig. 7), New Mexico, and western Texas separates the southern Laramide Rocky Mountains from the Colorado Plateau. This linear valley through which the Rio Grande flows southward to El Paso, and then southeastward toward Big Bend National Park, was formed during the same episode of extension of the Earth's crust as the Basin and Range Province, with which it connects in central New Mexico.

The rift valley is generally bounded by faults on one or both sides. Unlike the faults in the southern Basin and Range, many of those that bound the rift are still active, as shown by **fault scarps** that cut Quaternary gravels and glacial moraines. The rift is filled with hundreds to thousands of feet of Neogene gravel, sand, and clay (unit nT) interlayered with Neogene lava flows, chiefly basalt (unit nTv). Much of it is floored by Quaternary alluvium and wind-blown sand (unit Q). A number of volcanoes of Quaternary age punctuate the floor of the rift; none of these is currently active, but most of them still retain little-modified volcanic shapes. Opening of the rift led to uplift of the flanking ranges, so that many of the highest peaks in the conterminous United States lie along the rift margins in central and southern Colorado.

Paleogene Volcanic Fields of the Eastern Cordillera

During the Paleogene, following the end of the Sevier and Laramide orogenies, volcanic rocks (unit pgTv) were erupted in a number of volcanic fields in the Laramide Rocky Mountains, Colorado Plateau, Basin and Range Province, and Rio Grande Rift. In most places the eruptions started with **andesite** and similar lava from central volcanoes, together with **breccia** and **mud-flow** deposits. These early eruptions were followed by voluminous eruptions of volcanic ash with compositions resembling **rhyolite** that accompanied formation of great subcircular volcanic depressions called **calderas**. The calderas are thought to have been formed by the catastrophic collapse of the roofs of large near-surface bodies of granitic magma; the volcanic ash erupted was in many cases so hot and contained so much entrapped air that it flowed like a liquid (these deposits are known as **ash flows**). In many places the ash was hot enough to weld under its own weight when it came to rest, forming a hard, glassy rock called **welded tuff**. Some sheets of ash-flow tuff cover hundreds of square miles and have volumes of tens or hundreds of cubic miles.

The Paleogene volcanic fields were formed during an interval of about 30 million years, beginning at about 51 million years ago. However, their ages are not all the same. The eruptions began first in Idaho and northwestern Wyoming and progressed southward into northern Nevada, and then into central Nevada and southern Utah. Farther south, eruptions began in trans-Pecos Texas and progressed northwestward into the southern Rocky Mountains and southern Colorado Plateau and into the Sonoran subprovince of the Basin and Range in southern Arizona. These regular changes in the ages of the volcanic field are thought to be related to patterns of **subduction** of oceanic plates from the Pacific beneath western North America, but the exact mechanism is not yet clear.

The Challis volcanic belt (not labeled on the map) encompasses the Paleogene volcanic rocks (unit pgTv) east of the Idaho batholith in central Idaho. Early andesitic rocks were erupted there between 51 and 48 million years ago, and extensive rhyolite ash flows erupted from calderas between 48 and 45 million years ago. The ash flows were apparently fed from granitic bodies (unit pgTg) intruded into the Idaho batholith during the same time interval.

The Absaroka volcanic field lies in northwestern Wyoming, much of it in Yellowstone National Park. The volcanic rocks, chiefly andesitic lava, breccia, and mudflows (unit pgTv), were erupted from a chain of volcanoes between 50 and 43 million years ago, blanketing the older Laramide structures beneath thousands of feet of volcanic deposits. The Absaroka field is unique in that calderas and extensive ash-flow sheets are missing.

The Sierra-Wasatch volcanic field extends across Nevada and western Utah from the foothills of the Sierra Nevada to the Wasatch Range. Early eruptions, chiefly andesite and related rocks, began in the northern part of the belt between 41 and 38 million years ago. Andesite eruptions farther south began between 37 and 34 million years ago, and gave way to extensive ash-flow eruptions from calderas that lasted from about 34 to

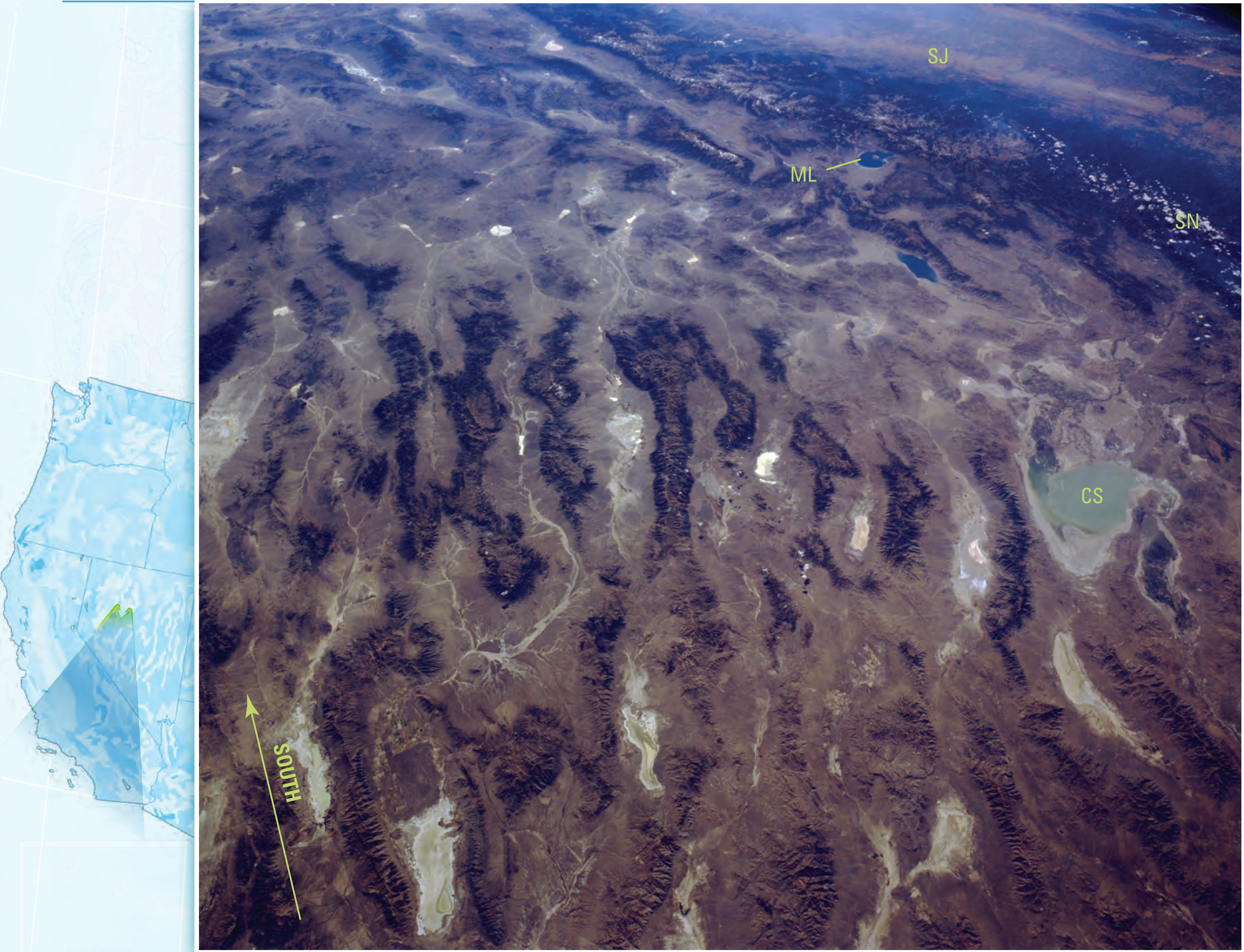
Figure 9. The Basin and Range Province, Nevada. View is southwest from near Carlin, Nev. This view shows much of the southern part of the Basin and Range Province. The dark mountains partly obscured by scattered puffy clouds seen near the upper right edge of the photograph are part of the Sierra Nevada (SN). Part of the San Joaquin (SJ) Valley in California is visible just beyond them. The nearly circular blue lake near the foot of the Sierra Nevada is Mono Lake (ML).

The parallel fault-bounded mountain ranges and intervening basins shown in the central part of the photograph are typical of the Basin and Range Province. The ranges are tilted blocks of Paleozoic and Mesozoic sedimentary rocks intruded by Cretaceous and Tertiary granite and capped by Tertiary volcanic rocks. The basins are filled with great volumes of sediment eroded from the neighboring ranges.

Most of the area pictured is within the Great Basin, a large closed basin from which nothing drains to the sea. The green area shown near the central part of the right edge of the photograph is Carson Sink (CS), where the Carson River, which drains part of the eastern slope of the Sierra Nevada, empties into a shallow basin, where it ponds and evaporates. The lighter-colored areas in the valleys between the ranges are playas where drainage from the nearby ranges collects and evaporates, leaving salty mud flats. At the time the photograph was taken a few of the playas apparently contained enough shallow water to glitter in the sun. During the Ice Ages much of this part of the Great Basin was filled with a huge freshwater lake known as Lake Lahontan, which covered 8,500 square miles and was as much as 900 feet deep.

Many of the range-bounding faults in this part of the Basin and Range Province are still active. On December 14, 1954, a magnitude-7.1 earthquake occurred near Fairview Peak, near the south end of the fish hook–shaped range visible near the center of the photograph. Four minutes later a magnitude-6.9 earthquake occurred along faults on the west side of Dixie Valley, the valley immediately east (left) of Carson Sink, forming scarps as much as 10 feet high.

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center; (photograph STS41G-121-184; available from http://eol.jsc.nasa.gov). Direction of view is southwest; altitude not given. Horizontal distance across center of area shown is about 250 miles.


SJ
ML
SN
CS
SOUTH

about 20 million years ago. By the end of the Paleogene eruptions, the ash flows formed a nearly continuous volcanic plateau that extended completely across the future site of the Basin and Range Province and that has since been dismembered by faults to form most of the ranges in the southern part of the Great Basin subprovince.

The San Juan volcanic field in southwestern Colorado is probably the best studied of all the Paleogene volcanic fields. It consists of andesite lava and breccia erupted from central volcanoes, chiefly between 35 and 30 million years ago, and great sheets of rhyolite ash-flow tuff that erupted from calderas between 31 and 25 million years ago. At least half a dozen major calderas have been recognized, and between 15 and 20 ash flows have been mapped, with volumes ranging from a few tens to hundreds of cubic miles.

The Mogollon-Datil volcanic field lies near the southeastern corner of the Colorado Plateau. The early andesitic rocks there were erupted starting about 49 million years ago, and extensive eruptions of rhyolite ash flows from calderas took place between 34 and 28 million years ago.

The Davis Mountains volcanic field lies in trans-Pecos Texas along the northeast flank of the Rio Grande Rift. Eruptions of andesitic rocks there began about 49 million years ago (about the same time as in the Challis and Absaroka fields) and gave way to eruptions of extensive ash flows between 38 and 32 million years ago. The volcanic field overlies rocks similar to those of the interior lowlands to the northeast, but these rocks were folded and faulted during the Laramide orogeny. Later the volcanic rocks were broken by faults related to the Rio Grande Rift. The Davis Mountains field is a northeastern outlier of the huge volcanic field of the Sierra Madre Occidental, which blankets much of north-central Mexico.

The same trend of younger ages to the north and west continues through Arizona into southeastern California, where the early andesitic rocks are as young as 27 million years old and ash flows and calderas range from 26 to 22 million years old. Thus, some of these rocks are shown as unit nTv on the map.

Accreted and Subduction-Related Terranes of the Western Cordillera

West of the Basin and Range Province and the Rocky Mountain fold and thrust belt many of the exposed Paleozoic and Mesozoic rocks are parts of **accreted terranes** that reached their present positions during the Mesozoic and Tertiary. Some of the accreted rocks originated in chains of volcanic islands, inter-island basins, volcanic plateaus, and seamounts that were lodged against the western edge of the continent as oceanic plates in the Pacific were subducted beneath the North American plate. Other parts of the collage of accreted terranes were probably parts of North America that were displaced laterally along the continental margin to reach their present positions. Studies of the fossils and of magnetic orientations of minerals in the accreted rocks suggest that many of them originally lay hundreds or even thousands of miles south of their present locations. Still other parts of the western tectonic collage consist of materials added to the western edge of North America, either as igneous rocks generated as tectonic plates from the Pacific were carried beneath the continent, or as sediments that accumulated in marginal basins related to the **subduction zones** and thrust eastward onto the continent.

The northern Cascade Mountains (A) extend across northern Washington from the San Juan Islands in Puget Sound to the Columbia River. The mountains consist chiefly of complexly folded and faulted sedimentary and volcanic rocks, chiefly of Mesozoic age, invaded by myriad granitic plutons of Mesozoic and early Tertiary age. Many of these rocks have been metamorphosed, and some have been converted to gneiss and **migmatite**. In the western part of this belt sheets of rocks have been carried westward along east-dipping thrust faults and all of the rocks have been displaced by steeply dipping faults, along many of which rocks west of the fault have moved northward with respect to rocks east of the fault.

Most of these rocks probably originated in island arcs or basins adjacent to them. **Paleomagnetic measurements** indicate that many of them originated thousands of miles to the south of their present positions. The rocks in the eastern part of the northern Cascade belt (the Okanogan Highlands) were probably added to North America late during the Paleozoic; those to the west were added during the Cretaceous.

The Olympic Mountains (B) and the Oregon and Washington Coast Ranges (C) lie between the Klamath Mountains and Vancouver Island in British Columbia. These mountains consist of a belt of Paleogene sedimentary and volcanic rocks (units pgT, pgTv). Most of the sedimentary rocks are mica- and feldspar-rich sandstone and siltstone and a few interlayered volcanic rocks that accumulated in an elongate marginal basin west of a chain of volcanoes, chiefly during the Eocene and Oligocene. The total thickness of these deposits is as much as 6,500 feet. To the east, these rocks interfinger with, and are overlain by, sediments deposited in shallow water or on land and with volcanic rocks related to the volcanic chain. Throughout most of the length of the basin the subduction zone lay offshore, but in the core of the Olympic Mountains, melange and associated rocks related to the subduction zone have been pushed under the rocks of the basin along thrust faults.

The rocks of the Blue Mountains (D) are similar to those in the northern Cascades. They are exposed in a discontinuous belt that includes the Blue Mountains of northeastern Oregon and extends northeastward to exposures in Hells Canyon on the Snake River between Idaho and Oregon.

The rocks include **intermediate** and **mafic** volcanic rocks (unit PzMzv); limestone, sandstone, and shale of Triassic age; and a belt of **melange** consisting of disrupted oceanic crust and deep-water sedimentary rocks of Paleozoic age that probably formed in a subduction zone (all of the sedimentary rocks and melange are grouped as unit PzMz). Paleomagnetic measurements indicate that many of these rocks also originated far to the south; they were transported northward and added to North America during the early Mesozoic. Such measurements also show that the rocks of the Blue Mountain belt were rotated about 60° clockwise since the Early Cretaceous. In western Idaho, rocks of the Blue Mountain belt are intruded by Late Cretaceous granitic rocks of the Idaho batholith.

A discontinuous chain of great volcanoes (E) forms the crest of the Cascade Range in Oregon and extends southward into northern California and northward across Washington into British Columbia. The most conspicuous volcanic vents are steep-sided cones of andesite lava and **pyroclastic** rocks, but these are interspersed with lower shield volcanoes that have erupted chiefly **basalt**. The lava and associated volcanic rocks of the Cascade chain are shown as unit Qv in Oregon, but in Washington they are not extensive enough to show on a map of this scale. The oldest eruptions in the volcanic chain started about 7 million years ago, but many of the volcanoes are still active, as confirmed by the explosive eruption of Mount St. Helens (fig. 10) in 1980. The Cascade volcanoes pose the most significant volcanic hazard in the conterminous United States. Although the eruptions themselves can be destructive, the greatest threats are volcanic mudflows generated by melting of glaciers and snowfields during an eruption that can course for miles down the flanks of the volcanoes and along river valleys into the urbanized lowlands nearby.

The Cascade volcanoes are a result of the continued subduction of the Juan de Fuca plate (part of the floor of the Pacific Ocean) beneath Oregon, Washington, and southern British Columbia. In places the volcanoes are built on older volcanic rocks marking the volcanic chain that existed during accumulation of the sedimentary rocks in the Coast Ranges to the west.

Most of the rocks exposed in the Klamath Mountains (F) in outhwestern Oregon and northeastern California and the northern Sierra Nevada (G) in east-central California formed in island arcs and adjacent basins, many of which originally lay far to the south. All of these rocks have been telescoped by movements along thrust faults, and in many places the thrust sheets are interleaved with large slices of **ophiolite** that represent the oceanic crust on which the arcs and basins formed. In most cases these thrusts root toward the west and movement of the upper plate has been toward the east, but in several cases the faults root to the east and movement has been toward the west. The westernmost of these displaced **terranes** closely resemble those in the western part of the Northern Cascades and the Blue Mountains and probably reached their present positions along the edge of the continent at the same time, during the early Mesozoic. The easternmost displaced terranes contain belts of Paleozoic rocks that probably originated in a volcanic archipelago along the margin of the continent and in shallow seas and deeper offshore basins. These terranes seem to have arrived in their present positions during the late Paleozoic or earliest Mesozoic, at the same time as some of the thrust faulting in the northern Basin and Range Province. In many places the accreted rocks were invaded by plutons of Jurassic and Early Cretaceous granitic rocks.

The Sierra Nevada batholith, the Great Valley **sequence,** and the Franciscan **Complex** (H) are quite different in their geology, but they are intimately related in terms of their history and tectonic setting and are therefore treated together in this discussion.

The Sierra Nevada batholith (1) is a belt of granitic rocks almost 300 miles long and as much as 70 miles wide that underlies the higher parts of the Sierra Nevada in eastern California. The batholith is part of a discontinuous band of granitic plutons that extends southward into the Coast Range of southwestern California and northward to include scattered plutons in northwestern Nevada and eastern Oregon and the Idaho batholith in Idaho and Montana. It may also include granitic plutons in the Northern Cascades in eastern Washington.

The Sierra Nevada batholith is not a single, huge body of granitic rock, but an amalgamation of literally hundreds of individual plutons that crop out over areas ranging from several square miles to hundreds of square miles. Although the batholith is shown on the map as Cretaceous granitic rocks (unit Kg), the age of the individual plutons ranges from Late Jurassic to Late Cretaceous. In general, the older component plutons lie along the western margin of the batholith and the plutons become younger in the eastern parts of the batholith. In the northern part of the batholith the plutons intruded accreted terranes of the northern Sierra Nevada and Klamath Mountains; farther south, they invaded Precambrian rocks that have been part of North America since the beginning of the Paleozoic, as well as their sedimentary cover rocks.

The plutons of the Sierra Nevada batholith and its extensions to the north and south represent the magma chambers that fed a chain of volcanoes resulting from subduction of tectonic plates of the Pacific beneath the western margin of North America, beginning in the early Mesozoic and continuing into the Late Cretaceous.

The Great Valley of California (2) is a flat-floored linear depression about 400 miles long and as much as 50 miles wide that occupies much of central California between the Sierra Nevada and the northern Coast Ranges. The valley is underlain by a sequence of Jurassic and Cretaceous sedimentary rocks, chiefly mudstone and sandstone that are referred to as the Great Valley sequence (shown as unit Mz on the map). The Great Valley sequence is largely covered by Neogene and Quaternary deposits that make up the floor of the present valley but is widely exposed along the margins of the valley, especially around its northern end. On the western side of the valley, the Great Valley sequence is locally nearly 10 miles thick and **dips** steeply eastward; on the east side the sequence is much thinner and dips gently westward. Detailed studies of the materials in the sand and mud show that the sediments of the Great Valley sequence were shed from the volcanic chain of the Sierra Nevada and from its roots and were deposited in a deep linear basin between the Sierra volcanic chain and a low, linear ridge to the west. Such **fore-arc basins** are common features of modern **convergent plate margins**.

The Coast Ranges of northern California lie west of the Great Valley and the Klamath Mountains and east of the San Andreas fault. The exposed rocks are coeval with the Great Valley sequence, but are quite different in character. Most of them belong to the Franciscan Complex (3), an enigmatic package of rocks that includes lower Mesozoic, Cretaceous, and Paleogene sedimentary rocks, chiefly dark shale and sandstone, but also basalt, chert, and metamorphic rocks of various kinds. Parts of the complex are melange, a chaotic mixture of blocks of sandstone, basalt, chert, and conglomerate in a matrix of dark, scaly mudstone. The blocks range from a few inches in diameter to hundreds of feet across. Unlike the Great Valley sequence, no orderly arrangement of layers is discernible in the Franciscan. The rocks are broken by pervasive low- and high-angle faults that destroyed any vestige of original layering and reduced the rocks to geological hash. Most rocks in the Franciscan have been metamorphosed to some degree, and some have been converted into **phyllite** and schist. In general, both the age and the degree of metamorphism increase eastward within the complex. In eastern parts of the Franciscan many of the rocks are **blueschist** that apparently formed at very high pressures but at moderate temperatures. The Franciscan is interleaved with sheets of dark mafic and ultramafic rocks that probably represent fragments of oceanic crust and that commonly lie along major thrust faults.

The contact between the Franciscan Complex and the Great Valley sequence is everywhere marked by faults. In many places the Franciscan seems to have been carried under the Great Valley rocks on a low angle thrust fault called the Coast Range thrust; in other places the two groups of rocks are separated by younger, steeply dipping faults along which there has probably been significant lateral movement.

The Franciscan is interpreted has having formed along an eastward-dipping subduction zone marked by a deep oceanic trench where tectonic plates of oceanic crust from the Pacific were being carried beneath the western edge of North America. The abundant low-angle faults, the melange, and the blueschist type of metamorphic rocks are thought to have formed as material eroded from the continent, fed into the trench, and was carried down the subduction zone.

Beginning about 29 million years ago, plate motions along the California segment of the Pacific Coast began to change from convergence of the ocean floor plates beneath the Pacific with the North American plate to northwestward movement relative to North America. This change led to the development of a complex array of northwest-trending strike-slip faults along which rocks on the southwest side moved

Figure 10. Mount Saint Helens, Washington. Mount Saint Helens is one of more than a dozen active volcanoes that lie along the crest of the Cascade Mountains between northern California and southern British Columbia. These volcanoes formed as a result of eastward subduction of the Juan de Fuca tectonic plate (which lies offshore beneath the Pacific Ocean) beneath the western edge of North America.

On May 18, 1980, this volcano erupted explosively after several months of premonitory activity, including swarms of earthquakes and ash and stream eruptions. In the weeks preceding the main eruption an unstable bulge formed on the north face of the mountain and continued to grow at a rate of as much as 5 feet per day. At about 8:30 a.m. on May 18 a magnitude-5.1 earthquake caused the bulge to collapse catastrophically, triggering a huge rock debris avalanche that surged north into and across Spirit Lake and west down the North Fork of the Toutle River at speeds estimated at 110–155 miles per hour.

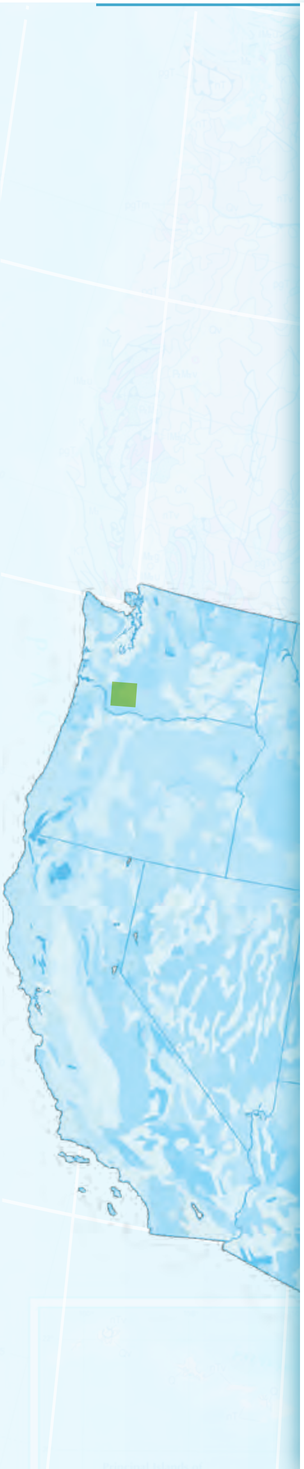
Within seconds after the avalanche, the sudden unloading of the mountain's north flank released the pent-up pressure on the volcanic system in an explosive northward-directed lateral blast that was heard hundreds of miles away. The shock wave from the blast, which traveled at speeds of more than 600 miles per hour, overtook the debris avalanche and spread out to the north and northwest, obliterating forests for as much as 8 miles from the volcano and flattening trees as far as 19 miles away.

Shortly after the lateral blast, a strong, vertically directed explosion spewed out a rising column of ash and steam that reached an altitude of 12 miles in less than 10 minutes. Traces of ash spread by the jet stream were recorded as far away as eastern Oklahoma. At the same time, dense flows of incandescent volcanic ash spread northward out of the breached crater, burying parts of the debris avalanche.

Within minutes after the start of the eruption, water from melting snow and glacier ice on the upper slopes of the mountain triggered mud flows of volcanic debris down the South and North Forks of the Toutle River and other streams draining off the volcano. Some of these flows reached depths of 66 feet and surged up valley walls as much as 350 feet. The eruption, which has been called one of the most significant geologic events in the United States during the twentieth century, resulted in 57 deaths, including that of David A. Johnston, a U.S. Geological Survey scientist who was monitoring the volcanic activity.

Annotations on the photograph show North Fork of the Toutle River (NF); South Fork of the Toutle River (SF), Spirit Lake (SL), and Coldwater Lake (CL). Numbers show volcanic deposits: debris avalanche deposits (1), volcanic ash flows (2), blast zone (3) and mud flows (4). Distance from the center of the crater to the northeast end of Coldwater Lake is about 8 miles.

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center; (photograph STS064-51-25; available from http://eol.jsc.nasa.gov). Direction of view is vertical; altitude not given. Taken September 1994.

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northwest with respect to those on the northeast side. The largest and most continuous of these faults is the San Andreas, which extends from the head of the Gulf of California to Cape Mendocino, more than 800 miles, about 200 miles of which is offshore between Point Reyes (fig. 11) and Cape Mendocino. The total offset along the San Andreas since 22 million years ago has been about 200 miles, but this represents only a fraction of the total displacement of the Pacific ocean floor relative to North America. The remainder of the movement is being taken up by movement on the myriad other faults of the San Andreas system and by extension of the crust in the Basin and Range province. The movements along the San Andreas and the other faults related to it have dismembered and displaced the previously assembled collage of tectonic terranes, greatly complicating the pattern of the geology, to the frustration of generations of geologists!

Southwest of the San Andreas fault in the southern Coast Ranges and Peninsular Ranges (l) is a diverse assemblage of tectonic terranes, some of which may have originated hundreds of kilometers south of their present positions. Much of the northward movement of these terranes apparently took place since the Paleogene but before the present San Andreas fault was established. Rocks in these terranes include metamorphosed sedimentary and volcanic rocks of Mesozoic age, Cretaceous granitic rocks similar to those in the Sierra Nevada batholith, and sedimentary rocks similar to those of the Great Valley sequence and the Franciscan Complex. Lateral movements along the northwest-trending San Andreas fault and its predecessors led to the development of a number of isolated basins in which a great thickness of Paleogene and Neogene sedimentary rocks (units pgT and nTg) accumulated. Many of these sediments have been complexly folded and displaced during continuing fault movements (fig. 12).

Lava Plains and Plateaus of the Columbia Intermontane Region

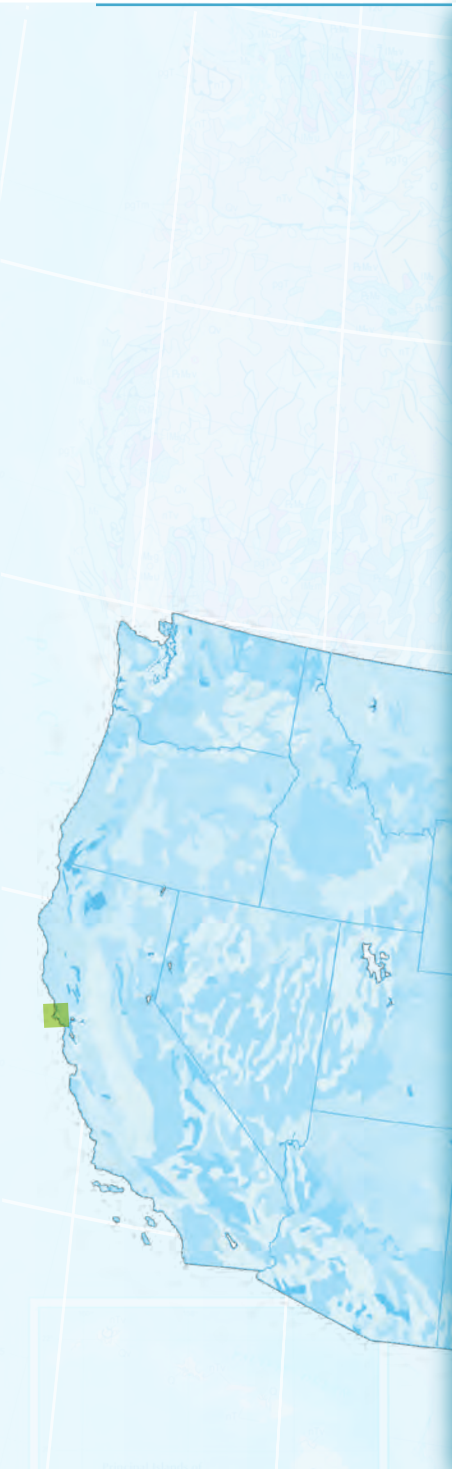
North of the Basin and Range Province, between the volcanic chain of the Cascades and the Idaho batholith, lies a vast region of plains and plateaus formed by flows of basalt (unit nTv) that accumulated since about 17 million years ago. The lava flows and layers of volcanic ash and sediment cover an area that exceeds 86,000 square miles; their total volume probably approaches 100,000 cubic miles. This region can be divided into three principal parts: the Oregon Plateaus, the Columbia River Plateau, and the Snake River Plain.

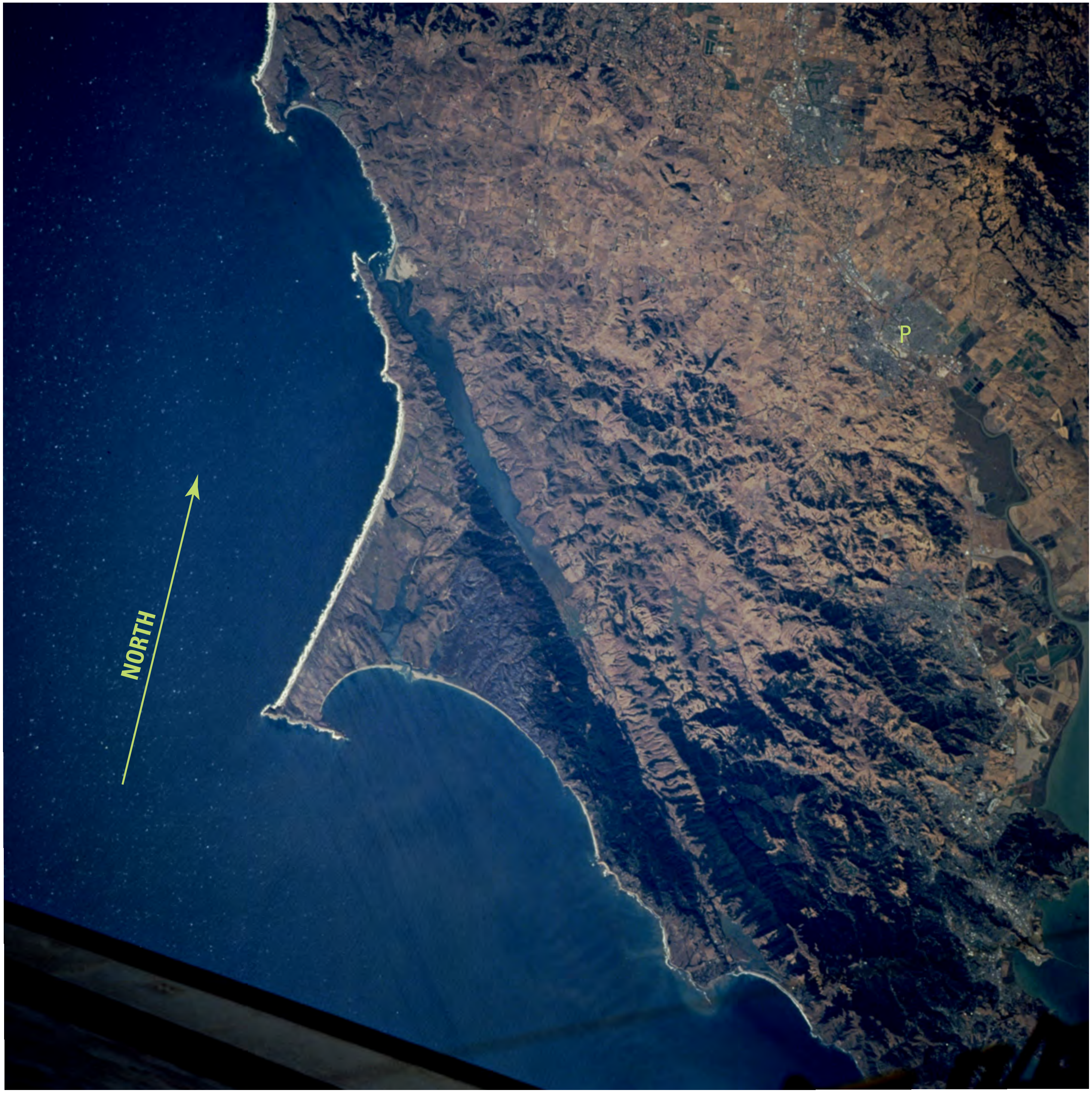
The Oregon Plateaus comprise the parts of the region south of the Blue Mountains and east of the Snake River Plain. They encompass most of southeastern Oregon and extend into northern California, northern Nevada, and southwestern Idaho. The plateaus are underlain by a thick sequence of lava flows and associated sedimentary rocks that accumulated largely between 17 and 14 million years ago in a deep basin that was open to the south, toward the Basin and Range Province. The lava is chiefly basalt erupted from deep linear fissures that seem to have formed at about the same time as the regional extension in the Basin and Range Province. In many places the volcanic rocks are cut by faults similar to those formed by extension in the Basin and Range. Although basalt predominates, rhyolite, erupted chiefly as volcanic ash from **calderas**, is also widespread.

Figure 11. The San Andreas fault at Point Reyes, California. The long, straight, northwest-trending depression that extends diagonally across the area of the photograph marks the San Andreas fault. Here the fault separates Late Cretaceous granite and nearly flat lying Tertiary sedimentary rocks on the southwest from rocks of the Franciscan Complex of Mesozoic (Jurassic and Cretaceous) age. The Franciscan is a chaotic mixture of blocks of sandstone, chert, and dark igneous rocks embedded in dark shale and sandstone. It accumulated along the western edge of North America as parts of the Pacific sea floor were being subducted eastward beneath the continent.

During the 1906 San Francisco earthquake Point Reyes moved as much as 16 feet northwestward with respect to the rest of North America. The town of Petaluma (P) is near the eastern edge of the area shown in the photograph.

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center; (photograph STS073-726-004; available from http://eol.jsc.nasa.gov). Direction of view is vertical; altitude not given. Horizontal distance across the area shown about 36 miles.




NORTH
P

The Columbia River Plateau lies in southeastern Washington and northern Oregon, between the Blue Mountains and the northern Cascades. It is also underlain by a deep basin in which thousands of feet of basalt lava flows and interleaved sedimentary rocks accumulated, mainly between 17 and 14 million years ago, but some as recently as 6 million years ago. Some of these flows spread westward down an ancestral valley of the Columbia River all the way to the sea. The basalt flows of the Columbia Plateau were also erupted from fissures perhaps related to Basin and Range extension. In south-central Washington the lava flows and the sediments interlayered with them are broken by young thrust faults and warped by folds that trend northwest–southeast.

The western part of the Snake River Plain is a northwest-trending, fault-bounded depression in southwestern Idaho that is filled with as much as 5,000 feet of interlayered river deposits, lake beds, and basalt of Neogene age capped by Quaternary basalt flows.

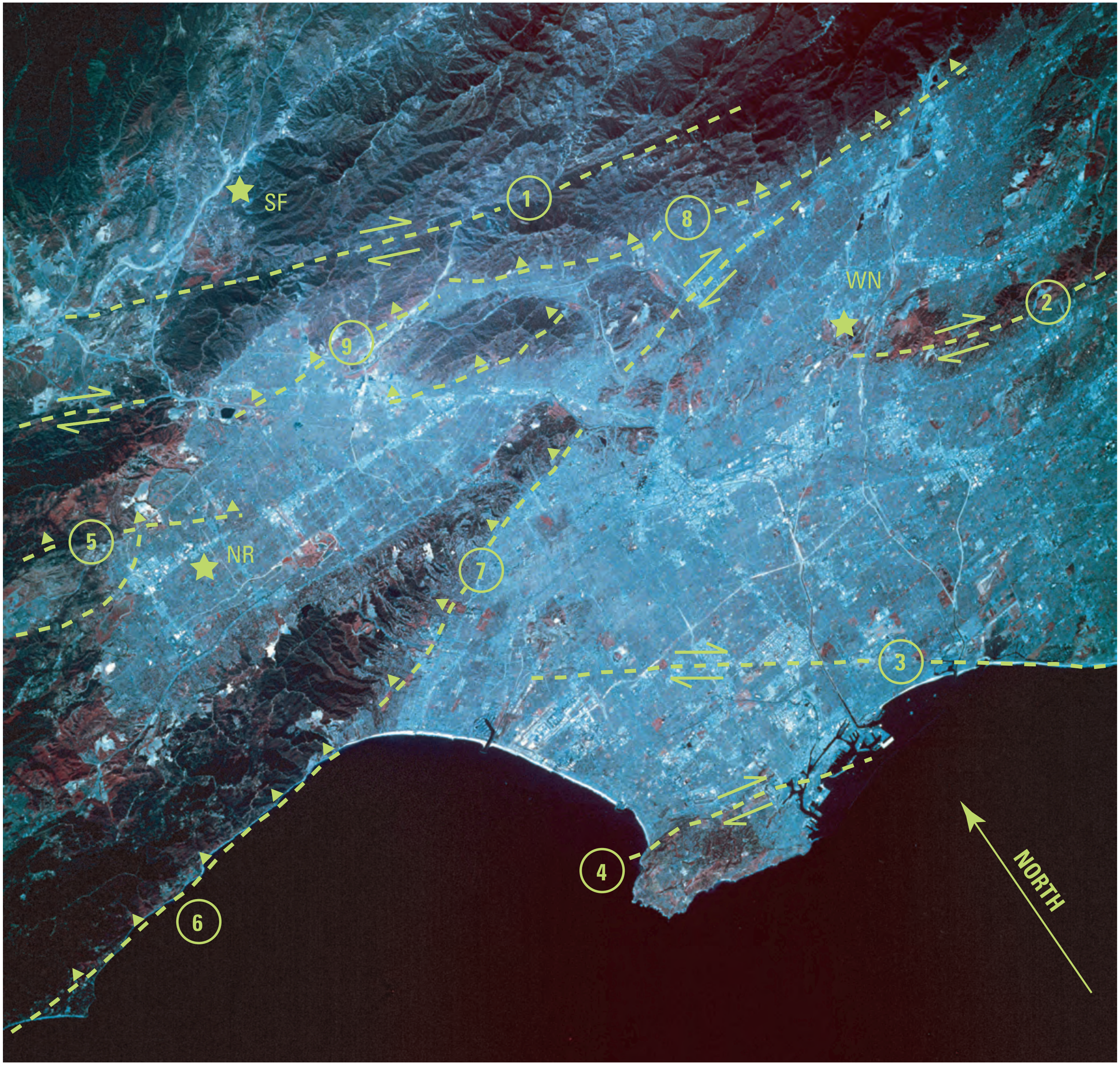
The eastern part of the Snake River Plain is a downwarp filled with volcanic rocks that trends northeastward from south-central Idaho into Yellowstone National Park, in northwestern Wyoming. The downwarp is largely floored by Quaternary basalt flows (unit Qv), but drilling shows that the basalt is underlain by great thicknesses of rhyolite volcanic ash erupted from calderas, some of which are buried beneath the younger basalt. The calderas range in age from 12 million years at the southwest end of the eastern plain to the still-active caldera in Yellowstone, which contains the world's largest active geyser field. The regular progression in ages from the oldest at the southwest to the youngest at the northeast has led to speculation that the eastern Snake River Plain marks the path of the North American plate across a stationary deep-seated plume of hot material rising from beneath the Earth's crust.

Figure 12. The Los Angeles Basin, California. The city of Los Angeles sits atop a deep basin filled with as much as 30,000 feet of very young sedimentary rocks, most of which were deposited as sediments on the sea floor, but some of which were deposited on land. The basin developed as a result of strike-slip movement on the San Andreas Fault, which lies just beyond the upper right corner of the area shown.

Just north of Los Angeles the generally northwest-trending San Andreas fault bends abruptly to the west-northwest for almost 150 miles, before bending back to the northwest. Northwestward movement of coastal California southwest of the fault causes compression and folding of rocks as the tectonic plate encounters the bend. The complex array of faults in and around Los Angeles is the result. The faults sketched on this photograph include northwest-trending strike-slip faults and east-trending thrust faults caused by compression. The strike-slip faults, such as the San Gabriel (1), Whittier-Elsinore (2), Newport-Englewood (3), and Palos Verdes (4), are roughly parallel to the San Andreas. They are marked with pairs of arrows indicating the relative motion of the rocks on either side of the fault. The compression-related thrust faults, such as the Simi (5), Malibu Coast (6), Santa Monica (7), Sierra Madre (8), and Oak Ridge (9), are decorated with small triangles that point in the direction of inclination of the fault and are placed on the side of the fault that moved up.

The Los Angeles Basin has been a prolific producer of oil, which was generated in the organic-rich sediments and trapped in folds and along faults. The active faults pose a significant hazard to lives and property. The approximate epicenters of the 1971 magnitude-6.7 San Fernando earthquake, the 1987 magnitude-5.9 Whittier Narrows earthquake, and the 1994 magnitude-6.7 Northridge earthquake are shown by stars labeled SF, WN, and NR. The focus of the San Fernando earthquake lay at a depth of about 5.2 miles along the San Fernando thrust fault. The focus of the Whittier Narrows earthquake was at a depth of 7.5 miles along a blind thrust related to the Whittier fault (a blind thrust is a thrust fault that does not reach the surface). The focus of the Northridge quake lay at a depth of about 4 miles along a south-dipping thrust fault.

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center; (photograph STS039-089-0062; available from http://eol.jsc.nasa.gov). Direction of view is vertical; altitude 141 nautical miles.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NORTH

Alaska

The vast State of Alaska, about one-fifth the size of the entire conterminous United States, has some of the most complex and poorly understood geology in North America. The State comprises a complicated collage of tectonic terranes (fig. 13) similar to those already described in the western cordillera of the conterminous United States. These terranes include displaced and (or) rotated fragments of the continental margin of North America, accumulations of volcanic rocks that were erupted during subduction of oceanic plates beneath North America, chunks of oceanic crust carrying **seamounts** and **oceanic plateaus** that were accreted to the margins of the continent, and extensive belts of sedimentary rocks that were deposited on oceanic plates and scraped off as they were pushed against the continental margin during subduction. Assembly of these disparate tectonic terranes began in the early Paleozoic and is continuing today. During and after **suturing** of the various terranes, thick sequences of sedimentary rocks accumulated in local or regional basins, concealing extensive parts of the terrane collage. Both the mosaic of tectonic terranes and the overlying basin rocks have been broken by large **strike-slip faults**. Some of these displace rocks on one side relative to those on the other side by hundreds of miles. For purposes of brief geological description, Alaska can be roughly divided into four regions: (1) Brooks Range and Arctic slope, (2) central intermontane plateaus and basins, (3) Aleutian–Alaska Range mountain system, and (4) the volcanoes of the Aleutian Islands, Alaska Peninsula, and Wrangell Mountains, and the Bering Sea volcanic field.

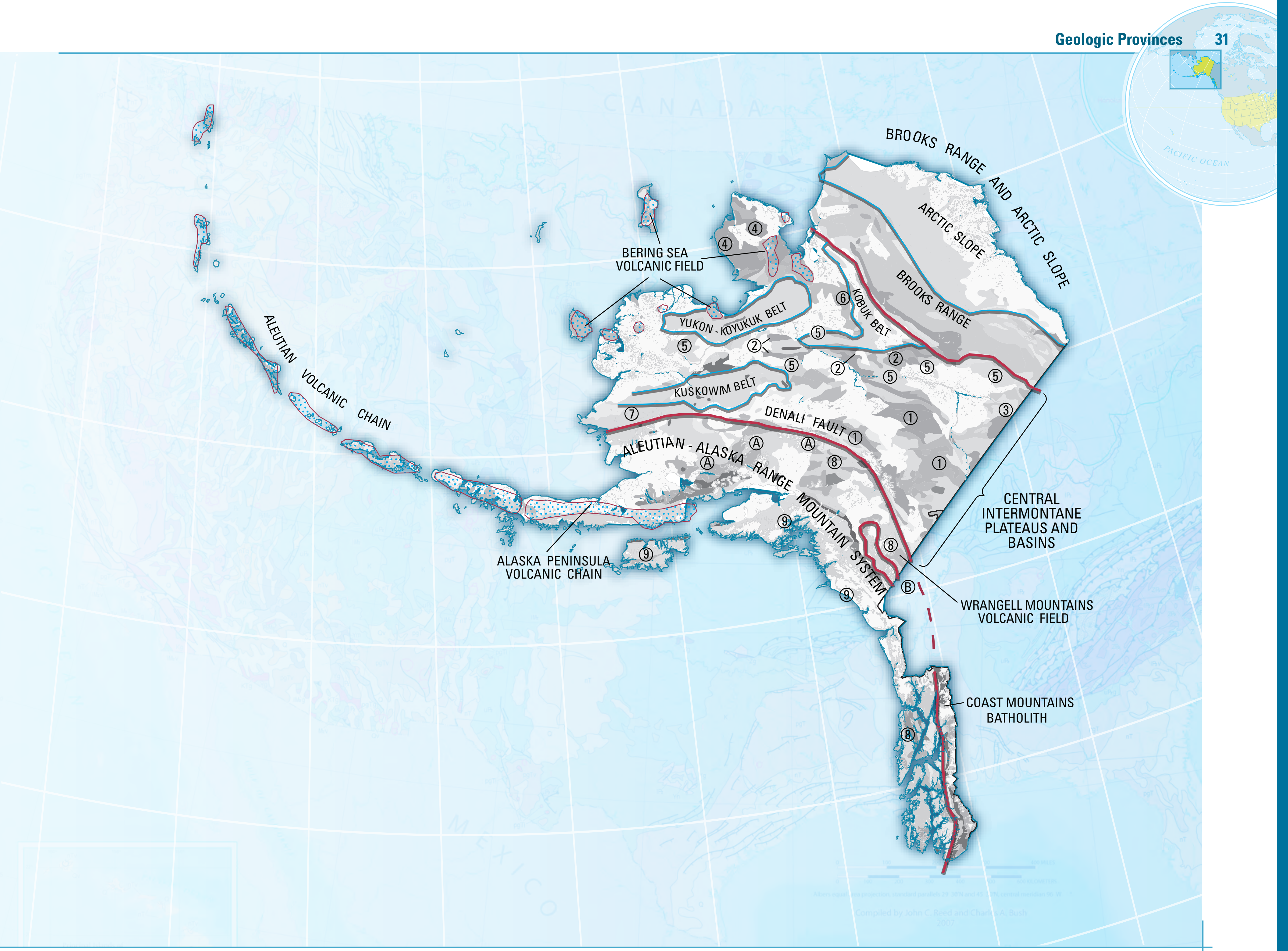
Brooks Range and Arctic Slope

The Brooks Range is the broad mountain belt that extends westward across northern Alaska from the Canadian border to the Arctic Ocean north of the Seward Peninsula. The Arctic slope includes the northern foothills of the Brooks Range and the Arctic coastal plain.

The Brooks Range consists largely of sedimentary rocks including Late Proterozoic and Paleozoic (Z, ZPz), lower Paleozoic (lPz), and middle Paleozoic (mPz) strata. These rocks are thought to have been part of the Arctic continental margin in western Canada that has been rotated 66° counterclockwise into their present position by sea-floor spreading in the Beaufort Sea during the Jurassic and Early Cretaceous. The rotation caused compression of the rocks on the leading edge of the rotating block, and this compression drove extensive sheets of rock northward along the thrust faults in the Brooks Range. Sediments shed northward from the rising mountains into the flanking basin (Mz, K) were themselves deformed into elongate east-west trending folds in the northern foothills. During this deformation many of the Paleozoic and Proterozoic rocks in the southern part of the range were complexly deformed and variably metamorphosed to gneiss, schist, slate, and phyllite.

The Arctic Slope north of the Brooks Range foothills is underlain by the Colville Basin, a deep basin filled with upper Cretaceous (K) and Tertiary rocks (pgT) that was depressed by loading of the Earth's crust by the thrust sheets in the range and the weight of the sediments shed from them. Much of the oil and gas production on the Arctic Slope comes from Paleozoic rocks buried beneath the Colville Basin. On the Arctic Coastal Plain the deposits in the Colville Basin are mantled glacial drift of late Tertiary and Quaternary age and by Quaternary and younger swamp deposits.

Figure 13. Index map showing geologic provinces and subprovinces in Alaska. Heavy red lines show boundaries between major provinces; medium-weight blue lines show boundaries of subprovinces and belts. In the central intermontane plateaus and basins province, circled numbers indicate general outcrop areas of some of the tectonic terranes mentioned in the text. Blue stipple shows late Tertiary and Quaternary volcanic provinces. In the Aleutian–Alaska Range mountain system province, circled letters show general positions of flysch basins mentioned in the text and circled numbers indicate outcrop areas of tectonic terranes.


PACIFIC OCEAN
CANADA
BROOKS RANGE AND ARCTIC SLOPE
ARCTIC SLOPE
BROOKS RANGE
KOBUK BELT
YUKON - KOYUKUK BELT
KUSKOWIM BELT
BERING SEA VOLCANIC FIELD
ALEUTIAN VOLCANIC CHAIN
DENALI FAULT
ALEUTIAN - ALASKA RANGE MOUNTAIN SYSTEM
ALASKA PENINSULA VOLCANIC CHAIN
CENTRAL INTERMONTANE PLATEAUS AND BASINS
WRANGELL MOUNTAINS VOLCANIC FIELD
COAST MOUNTAINS BATHOLITH
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Ⓑ
MEXICO
0 100 200 300 400 MILES
0 100 200 300 400 500 600 KILOMETERS
Albers equal area projection, standard parallels 29 30'N and 45 30'N, central meridian 96 W
Compiled by John C. Reed and Charles A. Bush
2007

Central Intermontane Plateaus and Basins

Interior Alaska, that part of the State that lies between the Kobuk-Malamute **strike-slip fault** at the southern edge of the Brooks Range and the Denali strike-slip fault at the northern front of the Alaska Range, comprises a vast region of low hills or plateaus and broad, sediment-filled basins and valleys. The region includes more than a dozen disparate tectonic terranes. Some are believed to represent rotated and translated fragments of the northwest-trending continental margin of North America that existed in the early Paleozoic or of sediments that were eroded from continental fragments and deposited on their flanks. Others are interpreted as containing rocks formed in and near arcuate chains of volcanoes that were accreted to the margin of the continent by subduction of oceanic crust. Still others are thought to be sheets of ocean floor and crust that were thrust onto the edge of the continent during the docking of the island-arc terranes.

The continent-related terranes include the Yukon composite terrane (1), the Ruby terrane (2), the Porcupine terrane (3), and the Seward terrane (4). They consist largely of metamorphic rocks like those in adjacent parts of North America, including highly deformed sandstone, schist, and marble (unit ZPz) and gneiss of Paleozoic age (unit Pzn). The rocks underlie metamorphosed Paleozoic and Mesozoic sedimentary rocks (units Pz and PzMz), and all of the rocks are invaded by large bodies of Cretaceous granite (unit Kg). The Porcupine terrane is apparently a fragment of the continental margin that lay near the hinge of the rotation that formed the Brooks Range and so escaped the major rotation. The Yukon composite terrane resembles the other continent-related terranes but is composed mainly of Paleozoic limestone (unit Pz) and upper Paleozoic and Mesozoic limey sandstone, siltstone, and shale (unit PzMz) that formed from sediments deposited in a shallow sea, probably on continental shelves.

Rocks shown on the map as unit PzMzv, forming a discontinuous, northeast-trending belt across central Alaska from Goodnews Bay to the Canadian border south of the Brooks Range, consist of highly deformed ocean-floor basalt and deep ocean sedimentary rocks, in many places interleaved with ophiolites (unit IMzu). These rocks are parts of the Angayucham terrane (5). They are believed to be dismembered fragments of ocean floor that was thrust onto the edge of the continent during closure of an ocean that lay to the west. They now overlie rocks of the Ruby terrane and Yukon composite terrane. Similar rocks also crop out in a narrow belt (too small to show on this map) along the southern edge of the Brooks Range and in thin sheets that have been shoved northward across the sedimentary strata of the range.

The Koyukuk (6) and Togiak (7) terranes comprise volcanic rocks and associated volcanic-rich sedimentary rocks (units Mzv and Mz). The volcanic rocks have compositions of rocks typically erupted along volcanic chains on the ocean floor (like the Aleutian Islands), and these terranes are thought to be parts of a volcanic arc that was accreted to North America during the closure of the ocean marked by the Angayucham terrane.

The tectonic terranes are separated and in part overlain by belts of sedimentary rocks, chiefly thinly interbedded dark argillite, siltstone, dark sandstone, and impure limestone, that originated as deposits in basins and troughs between the tectonic terranes as they were being assembled. Much of the sandstone contains fragments of volcanic rocks, and volcanic rocks are interlayered with the sedimentary rocks. Rocks in many parts of these belts were deformed and metamorphosed during terrane amalgamation and were invaded by bodies of granite and other plutonic rocks. Three of the principal belts of this sort are indicated by name on the map:

- The Yukon-Koyukuk belt, which consists of strongly deformed and mildly to strongly metamorphosed rocks of Early and Late Cretaceous age.
- The Kobuk belt, which consists of strongly deformed and variably metamorphosed rocks containing scattered mid-Cretaceous fossils.
- The Kuskokwim belt, which contains rocks similar to the other belts, but also some conglomerate. The rocks are generally mildly to moderately deformed but are little metamorphosed.

Assembly of the tectonic terranes started in the Late Jurassic and was largely completed by the Late Cretaceous, although later movement along major right-lateral strike-slip faults has significantly modified their Late Cretaceous configuration. Broad basins filled with Tertiary and Quaternary rocks formed after terrane assembly and are relatively undeformed.

Aleutian–Alaska Range Mountain System

The Aleutian–Alaska Range mountain system is a great mountain belt that extends in a broad, convex-northward, arcuate belt from the Aleutian Islands through the Alaska Peninsula, across southern Alaska and eastward through the southwestern part of the Yukon Territory of Canada and into southeastern Alaska. It includes some of the highest and most rugged peaks in North America. The belt consists largely of two principal groups of tectonic terranes: a group north of the Border Ranges fault system known as the Wrangellia composite terrane (8), and a group south of the fault system known as the Southern Margin composite terrane (9).

The Wrangellia composite terrane (8) consists chiefly of volcanic and sedimentary rocks that accumulated in or near several belts of midocean volcanic islands, possibly beginning in the Proterozoic, but continuing through the Paleozoic and much of the Mesozoic. The location of these islands at the time of accumulation is unknown, but paleomagnetic studies suggest that they may have originated hundreds or thousands of miles south of their present positions and that they were carried northward on tectonic plates that were being subducted under North America.

The Southern Margin composite terrane (9) is made up largely of sedimentary and volcanic debris that was deposited on the sea floor along the southern margin of Wrangellia. In the Middle Triassic (about 230 million years ago) subduction began to carry parts of the sea floor beneath Wrangellia. As a result, a trench in the sea floor developed and chains of volcanoes developed inland from the subduction zone. Great thicknesses of dark argillite and muddy sandstone, composed of material eroded from Wrangellia and from the volcanic chain that fringed it, accumulated in the trench, where they mixed with volcanic debris. These **flysch** deposits were then scraped off the oceanic plate and added to the southwest margin of Wrangellia as the oceanic plate was subducted beneath it. Much of the off-scraped material formed melange, a jumbled mixture of various sized blocks of rocks of all types, some from the sea floor and some from nearby continental areas, all enclosed in fine-grained sedimentary material. Generally, the melange is intensely deformed and weakly metamorphosed.

At the same time that subduction was taking place along the southwest margin of Wrangellia, Wrangellia itself was moving northward. By the time the Wrangellia composite terrane arrived in its present position sometime between 120 and 84 million years ago, it was already carrying parts of the Southern Margin composite terrane piggyback along its trailing edge. After the Wrangellia composite terrane docked with North America, subduction continued along its southern margin and material is still being added to the Southern Margin composite terrane as the Pacific plate continues to move northward along the coast of southeastern Alaska (fig. 14) and beneath the Alaska Peninsula.

The arrival of Wrangellia against North America was accompanied by intense deformation and metamorphism of rocks in the flanking terranes that were already part of the continent. Flysch deposits that had accumulated in basins in the ever-narrowing seaway that lay between the continental margin and the approaching landmass of Wrangellia were crammed against the continent to form a discontinuous belt of highly deformed dark sandstone, shale, and volcanic rocks that marks the inner edge of the Wrangellia composite terrane. The belt includes the Kantishna belt (A) and the Gravina-Nutzotin belt (B).

During the arrival of the Wrangellia composite terrane adjacent parts of the continent inboard of Wrangellia were invaded by great batholiths of granite, including those that make up the Coast Mountains batholith in the northeastern part of southeastern Alaska and adjacent parts of Canada, the granite bodies that make up much of Mt. McKinley (fig. 15) and its neighbors in the central Alaska Range, and most (but not all) of the granitic bodies in the Aleutian Mountains northwest of Cook Inlet.

Volcanoes of the Aleutian Islands, Alaska Peninsula, and Wrangell Mountains, and the Bering Sea Volcanic Field

Alaska has several Tertiary and Quaternary volcanic chains and volcanic fields, and many active or recently active volcanoes. The volcanic belt that includes the Aleutian volcanic chain, the Alaska Peninsula volcanic chain, and the Wrangell Mountains volcanic field developed as a result of subduction of oceanic plates beneath the Alaskan margin of North America. The current rate of movement of the Pacific plate relative to North America is a little less than 3 inches per year. The direction of movement of the Pacific plate is perpendicular to the volcanic arc in the area of the Alaska Peninsula, but because of the curvature of the arc the motion becomes nearly parallel to the arc in the westernmost part of the Aleutian Islands. The Wrangell Mountains, in the southern part of eastern Alaska (northwest of the point where the Alaska Panhandle joins the main part of Alaska) are part of the same volcanic chain but are separated from the main belt by a gap of about 250 miles. By contrast, the Bering Sea volcanic field seems to be related to crustal extension in western Alaska and the Bering Sea shelf.

The Aleutian volcanic chain is the emergent part of a largely submerged volcanic mountain range. The volcanic peaks stand above the sea surface to form the Aleutian Islands. These undersea mountains were built by volcanic activity beginning about 50 million years ago during the Eocene. The volcanic activity waned between about 35 and 5.5 million years ago and then resumed. The many currently active volcanoes were all built during this last time interval.

The Alaska Peninsula volcanic chain differs from that in the Aleutians to the west in that it was built on **continental crust** rather than **oceanic crust**. In the Alaska Peninsula most of the volcanic rocks overlie rocks of the Peninsular terrane (part of the Southern Margin composite terrane) or on Mesozoic granite plutons that intrude them. Most of the older volcanic rocks were erupted between 48 and 22 million years ago. A second period of volcanism started about 15 million years ago, but most of the active volcanoes and calderas have formed in the last million years, many within the last few thousand years.

The Wrangell Mountains are a group of voluminous shield-like volcanoes that have eruption rates among the highest reported for plate-margin volcanic fields. The volcanic field includes several peaks with elevations more than 16,000 feet. The ages of volcanic activity generally decrease from 15–20 million years in the eastern part of the field to 1–5 million years in the central part, and to 1 million years in the western part. The volcanoes have no recorded historic activity, but a vent in the field was the source of two eruptions that spread ash over wide areas in Alaska and Canada 1,890 and 1,250 years ago.

Figure 14. Glacier Bay and the St. Elias Range, Alaska. The St. Elias Range marks the boundary between Alaska and the Yukon Territory along the northwestern part of Alaska's southeastern panhandle. The highest peak in the range, 18,000-foot Mount St. Elias, lies just north of the area shown. Glacier Bay is a multibranched fjord visible in the lower right part of the photograph, and Icy Strait is visible along the lower-right edge.

The Border Ranges thrust fault shown in the central part of the photograph marks the suture between the Wrangellia composite terrane on the east and the Southern Margin composite terrane on the west. The rocks east of the fault are chiefly middle and lower Paleozoic gray sandstone, argillite, limestone, and volcanic rocks, all of which are intruded by large, irregular bodies of Cretaceous and Tertiary granite. Those west of the fault are chiefly metamorphosed Cretaceous sandstone, argillite, and basalt cut by Tertiary granite and other igneous rocks.

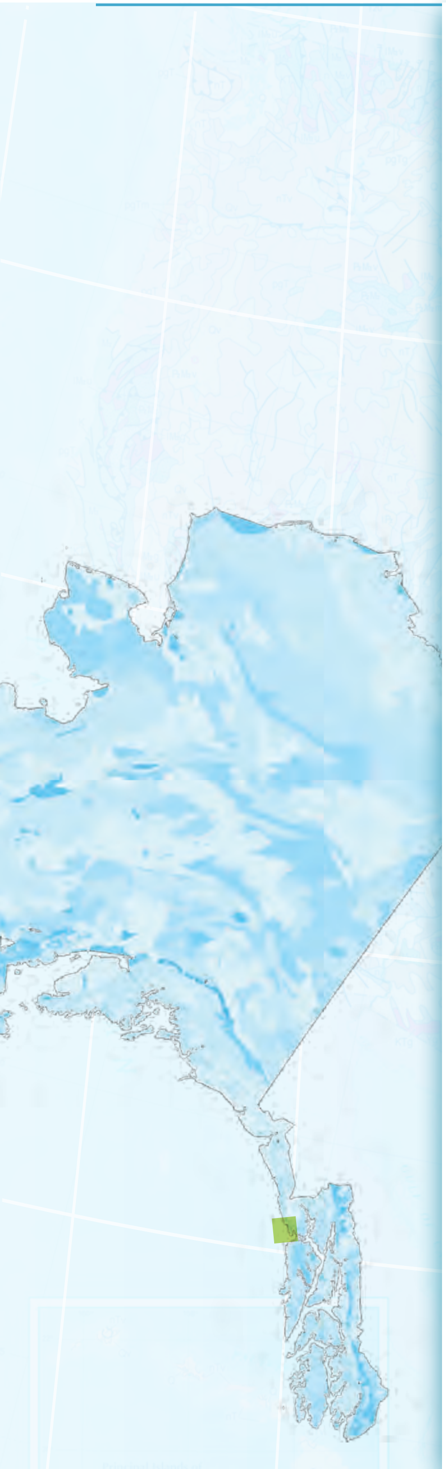
The Fairweather fault shown in the left part of the photograph is an active strike-slip fault that has displaced part of the Wrangellia composite terrane northward relative to the rocks of the Southern Margin composite terrane. In 1958 an earthquake along the Fairweather fault triggered a huge rock slide that plunged about 3,000 feet into the head of Lituya Bay, causing a wave that surged up the opposite wall of the inlet to an altitude of 1,740 feet!

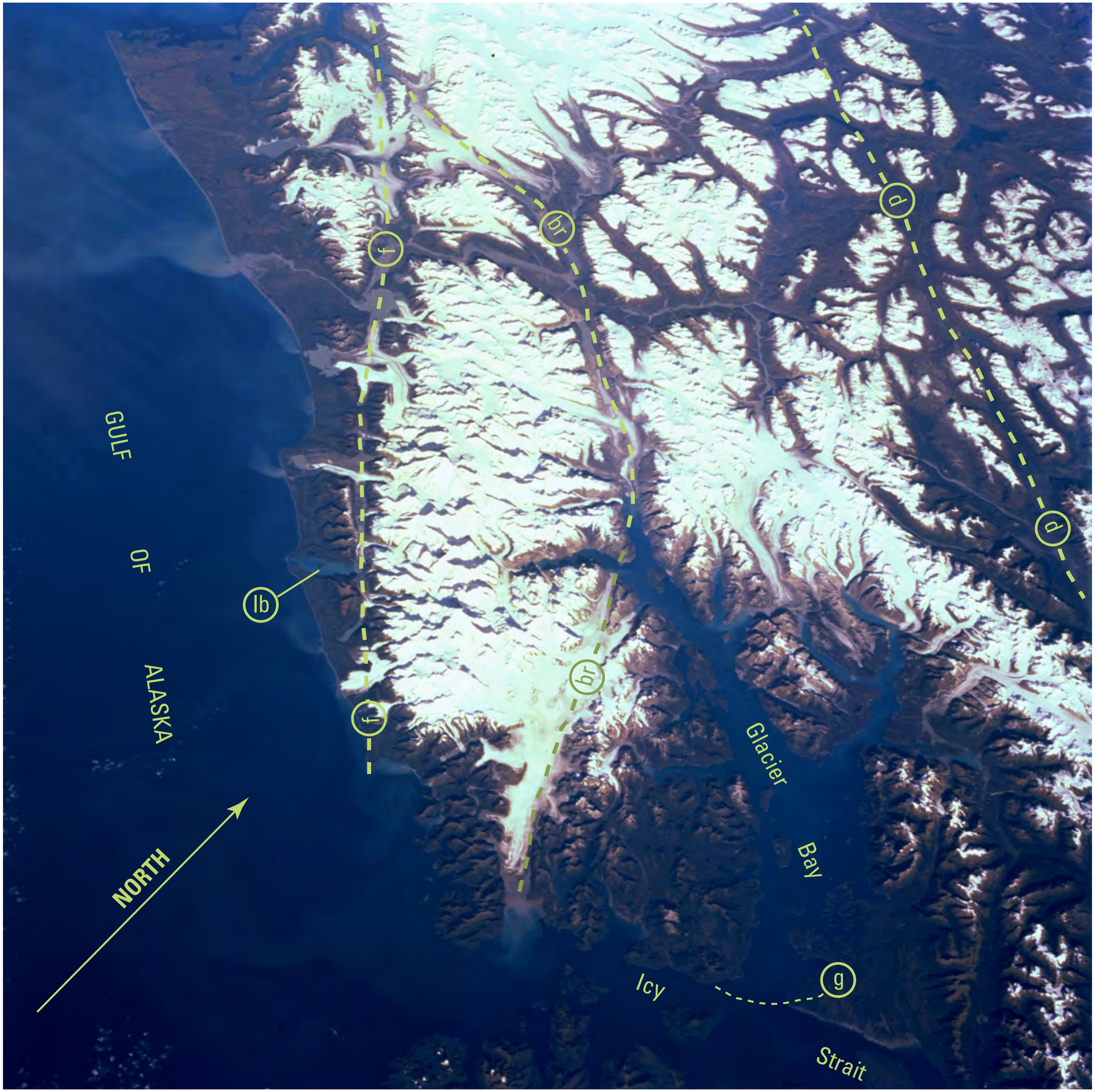
Part of the Denali strike-slip fault, which separates the Wrangellia composite terrane from the Yukon composite terrane, is visible in the upper-right corner of the photograph.

When Vitus Bering explored Icy Strait in 1742, glaciers extended all the way to the mouth of Glacier Bay. Since that time the ice front has retreated more than 60 miles, and most of the glaciers are continuing to retreat. Strangely, however, a few seem to be advancing slightly, probably due to local shifts in storm tracks.

Annotations on the photograph show the Border Ranges fault (br); Fairweather fault (f); Denali fault (d); Lituya Bay (lb); and position of glacier terminus at mouth of Glacier Bay in 1742 (g).

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center; (photograph STS068-229-7; available from http://eol.jsc.nasa.gov). Direction of view is vertical; altitude not given. Horizontal distance across center of the area shown is about 110 miles.




f
f
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The Bering Sea volcanic field differs from the other volcanic areas in that its volcanic rocks consist almost entirely of basalt, whereas the subduction-related volcanic rocks are largely andesite or rhyolite. Most of the volcanic rocks are less than 5 million years old, and some lava flows and cinder cones are less than 10,000 years old, but none is active at present. Much of the lava was erupted from clusters of low shield volcanoes or from fissures in the underlying rocks.

Figure 15. Mount McKinley, Alaska. View from the south from over the Gulf of Alaska with an 800-mm lens. Mount McKinley, often referred to by its native name, Denali, is the highest mountain in North America. The South Peak, altitude 20,320 feet, is marked with an arrow on the photograph; the slightly lower North Peak is visible behind and slightly to the left. McKinley and its towering neighbors, including 17,400-foot Mount Foraker (F) and 13,200-foot Mount Silverthrone (S), are carved from large bodies of Tertiary granite that intruded intensely deformed dark sandstone, argillite, and volcanic rocks along the northern edge of the Wrangellia composite terrane. These rocks were uplifted by movements along the Denali fault, which lies just north of the high peaks but is out of sight in this photograph. Mount McKinley lies near the apex of a major bend in the fault where its trend changes from west-northwest to southwest. Horizontal movement along the fault carried the rocks south of the fault westward with respect to the rocks to the north. As they encountered the bend, the rocks were forced up and northward. Erosion of these uplifted rocks, largely by glaciers, removed the softer, more easily eroded sedimentary rocks and left the massive granite bodies standing as some of the continent's highest peaks.

In this photograph, taken in August 2005, the valleys are partly obscured by a pall of smoke from widespread forest fires. However, several of the large glaciers that flow southward from the Alaska Range toward the Chulitna River are visible, including the Kahiltna (K), Tokositna (T), and Ruth Glaciers (R). The Kahiltna Glacier is about 45 miles long, making it the longest in the Alaska Range.

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center; (photograph ISS011-E-11805; available from http://eol.jsc.nasa.gov). Direction of view is north; altitude 188 nautical miles.


F
S
R
K
T
R

Hawaii

The State of Hawaii consists of a chain of islands (fig. 16) that represent the emerged summits of a huge northwest-trending submerged volcanic ridge. The large islands at the southeastern end of the chain extend for about 400 miles northwestward from the Island of Hawai'i to Ni'ihau, but small islands and reefs included in the State extend another 930 miles westward, so that the total length of the island chain in the State is only slightly less than the distance from Washington, D.C., to Denver, Colo. However, the total land area of the State is only about 6,600 square miles, about the size of Connecticut and Rhode Island combined. The volcanic ridge continues northwestward to beyond Midway Island and then turns northward at the totally submerged Emperor Seamounts and extends almost to the western tip of the Aleutian Islands.

The sea floor on which the volcanic ridge is built ranges in depth from about 15,000 feet near the large islands to about 17,000 feet around the small islands to the northwest. The age of the sea floor on which the ridge stands is between 120 and 80 million years. However, the age of the basalt flows that make up the major part of the larger islands increases regularly from less than 400,000 years on Hawai'i (where the volcanoes Kilauea, Mauna Loa, Mauna Kea, and Hualalai are still active) to about 5 million years on Ni'ihau and Kaua'i (the northwesternmost of the large islands). The same trend continues to the northwest—the lava on Midway Island was erupted almost 28 million years ago. The northwestward increase in the ages of the volcanoes that make up the island chain is thought to be related to passage of the Pacific plate northwestward across an area of high temperature caused by upwelling of hot material from a stationary source deep within the Earth. As the Pacific plate moves across the hotspot it is melted to form the lava that builds the volcanic ridge. The situation might be likened to slowly moving an old wax phonograph record across a blowtorch flame. If the record moves northwest across a stationary flame, an ant on the surface of the record would observe that from his point of view the zone of melting is progressing southeast. As a volcanic center is moved northwest away from the hotspot, volcanic activity ceases and streams and waves erode the volcanic edifice. At the same time, cooling of the volcanic material causes the rocks to contract and become denser, causing the volcanic pile and the surrounding ocean floor to subside. Thus, the islands become smaller and more deeply eroded toward the northwest along the island chain and eventually are reduced to coral atolls.

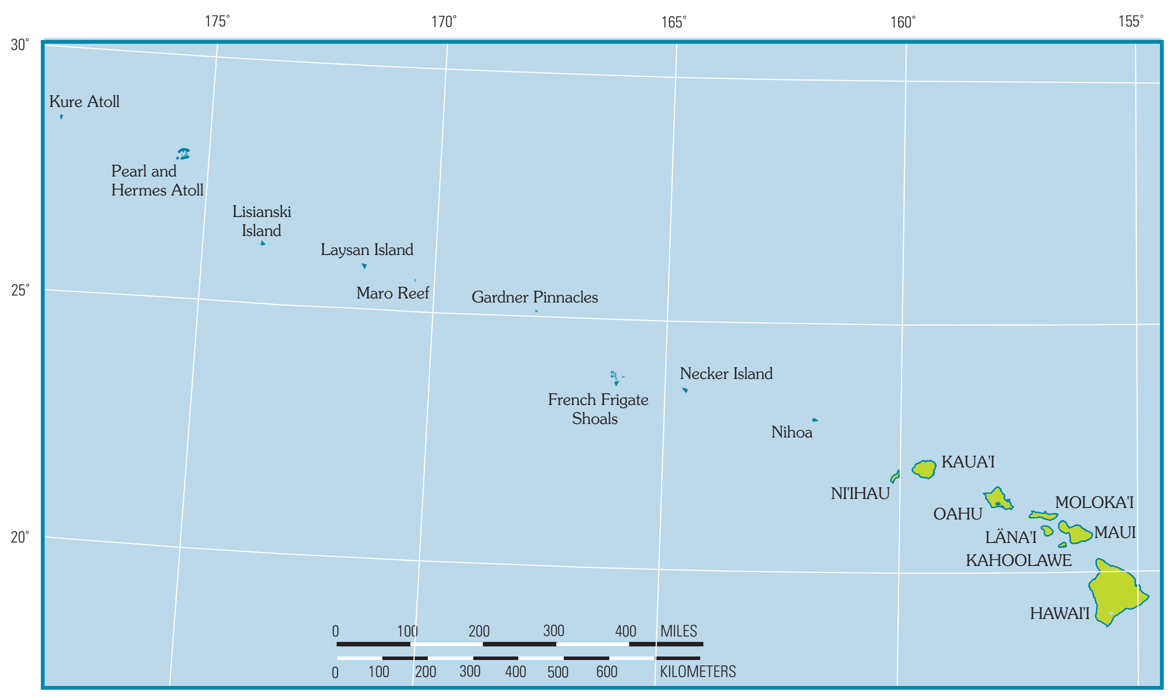


Figure 16. Index map showing the chain of islands that makes up the State of Hawaii.

Puerto Rico and the U.S. Virgin Islands

Puerto Rico and the U.S. Virgin Islands lie just south of the plate boundary between the Caribbean plate and the North American plate. The islands are largely composed of volcanic rocks and closely related sedimentary rocks (unit Kv). Most of these rocks are of Late Cretaceous age, but some are Early Cretaceous and some are as young as Paleogene (unit pgTv). All these rocks probably accumulated in and among arcuate chains of volcanic islands that developed along the plate boundary. Near the southwestern tip of Puerto Rico are several small areas of ultramafic rocks (unit u) thought to have been pieces of old ocean floor that were shoved onto piles of volcanic rock fragments as the plates were jostled into their present positions. The volcanic-sedimentary rock sequence has been partly dismembered by a complex series of west-northwest-trending faults along which rocks on the north side of the fault have moved west relative to those on the other side. The sequence has also been intruded by large plutons of granite that are shown as unit Kg on the map, but some of which may be of early Tertiary age. Along the northwestern and southwestern coasts of Puerto Rico the older rocks are covered by younger sedimentary rocks, chiefly limestone, shown as unit nT on the map.

The Puerto Rico trench, which lies about 160 kilometers off the north coast of the island, marks the present southern boundary of the North American plate, and frequent earthquakes along the trench show that significant movement is still taking place along the plate boundary.

Faults

Faults are fractures or fracture zones along which rocks on one side have moved significantly with respect to those on the other side. Most faults shown on the geologic map layer have displacements of miles or even hundreds of miles, but some, such as those in the Gulf Coastal Plain, have displacements of only a few feet. Wherever possible, faults shown on the geologic map are classified on the basis of the inclination of the fault surface and the relative direction of offset of the rocks on either side. A normal fault is a steeply inclined fault along which the rocks above the fault have moved downward with respect to those below the fault. A thrust fault is a gently or moderately inclined fault along which the rocks above the fault have moved upward with respect to those below the fault. A low-angle detachment fault is a gently inclined or horizontal fault formed during the pulling apart of brittle rocks in the upper parts of the continental crust accompanied by rise of warmer, more plastic rocks beneath to form dome-shaped uplifts. The remaining faults on the geologic map ("Fault" in the legend) are not classified, either because the sense of displacement is unknown, or because they are too short or too closely spaced to allow placement of distinguishing map symbols. All strike-slip faults (steeply inclined faults along which the rocks on opposite sides are displaced horizontally) are included with the "unclassified" faults on the geologic map. Most of the faults shown on the geologic map are inactive, and many have not moved for millions or tens of millions of years.

The faults shown on the layer of the National Atlas entitled "Quaternary faults" are faults along which large-magnitude earthquakes have occurred within the past 1.8 million years. These faults may be capable of generating future earthquakes having magnitudes of 6 or greater. Large-magnitude earthquakes in the Western United States produce displacements during a single earthquake that are generally a few feet, but cumulative Quaternary displacement across a fault may be several miles for normal faults, such as the Wasatch fault near Salt Lake City, and as much as tens of miles for major plate-bounding faults, such as the San Andreas fault. Many Quaternary faults in the Western United States coincide with faults shown on the geologic map. However, large-magnitude earthquakes in the less seismically active Eastern and Central United States commonly do not produce surface deformation. Therefore, most historical major earthquakes do not coincide with faults shown on either the geologic map or the Quaternary fault layer. Additional information on potential earthquake faults is available at http://earthquake.usgs.gov/regional/qfaults. Currently (2007), the Quaternary fault database covers faults in the conterminous United States, but information on faults in Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands will eventually be added.

Continental Ice Sheets

Continental ice sheets have advanced southward from Canada into the Central and Eastern United States a dozen or more times in the past 2 million years (fig. 17). The most recent of these, the Wisconsin glaciation, reached its maximum extent about 20,000 years ago and had retreated by about 10,000 years ago. The map shows the approximate maximum extent of the Wisconsin ice, but the ice may not have reached this limit everywhere at the same time. The map also shows the maximum southern extent of ice sheets older than the Wisconsin, but the margins shown on the map may represent ice advances of very different ages.

Although ice-laid surficial deposits are widespread north of these glacial limits, stream-laid and windblown deposits related to these glacial advances extended hundreds of miles farther south. None of these deposits is shown on the map, but they are shown in detail on the map of surficial deposits and materials in the Eastern and Central United States that is part of the National Atlas.

The limits of mountain glaciers in the Cordillera could not be depicted on the present map because their extreme complexity would obscure the bedrock geology, which is the primary focus of the map.

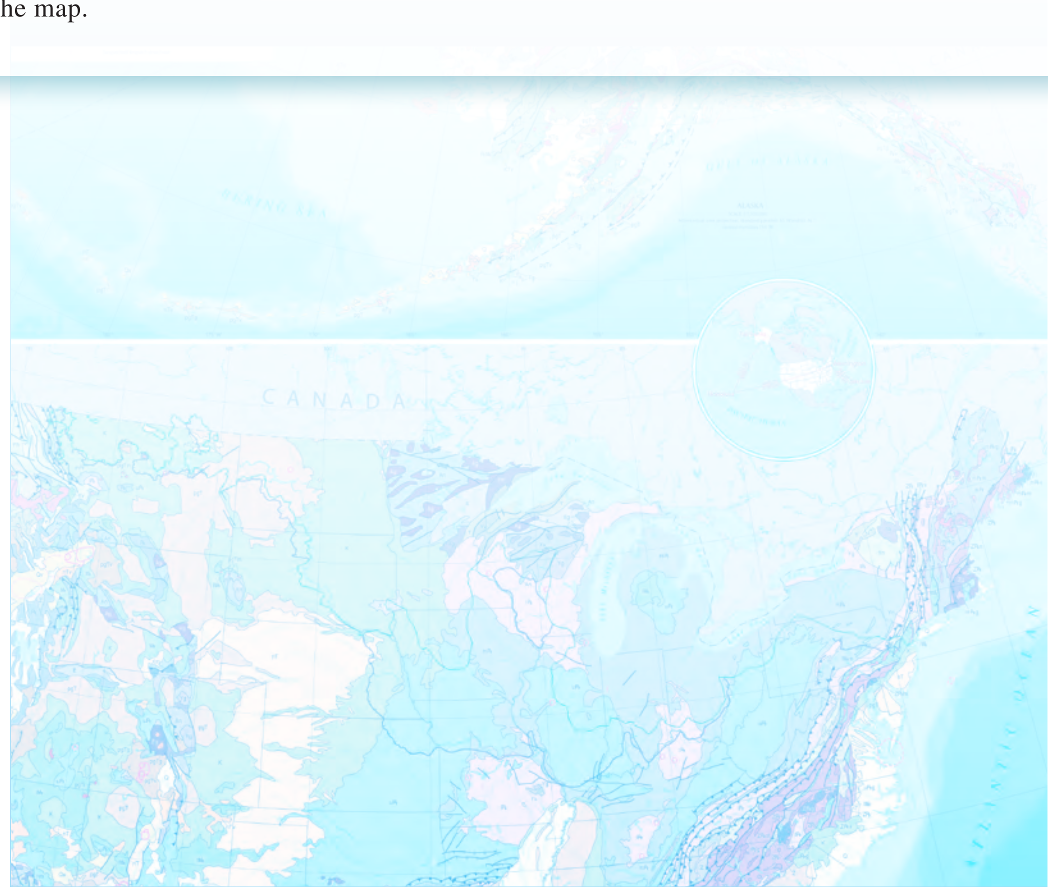


Figure 17. Edge of the continental ice sheet in South Dakota. View is west-northwest over Pierre, S. Dak. (P). Lake Oahe is impounded by the Oahe Dam across the Missouri River just upstream from Pierre. The western arm of the lake that extends nearly to the top of the photograph is the drowned valley of the Cheyenne River; the rest of the lake is the drowned valley of the Missouri.

The checkerboard pattern marks farmlands that have been divided into tracts according to townships and sections. The green circles north of the dam mark areas of sprinkler irrigation fed by groundwater pumped from shallow wells at the center of each circle. Most of the circles are one-quarter mile in diameter.

About 12,000–13,000 years ago the western edge of a large lobe of the great glacier that covered most of the north-central states lay 5–10 miles southwest (left) of the river. The approximate position of the ice front is marked with a dashed line on the photograph; ticks on the line point toward the ice. The farmlands west of the ice front are underlain by gravel carried by streams flowing off the melting glacier and by weathered, flat-lying Cretaceous shale and sandstone. The conspicuous streaks are ridges of windblown silt carried by northwest winds blowing off the ice-sheet farther north. The checkerboard of cultivated fields east and north of the river is underlain by silt, sand, and gravel deposited as the glacier stagnated and melted.

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center; (photograph STS028-076-056; available from http://eol.jsc.nasa.gov). Direction of view is west-northwest; altitude 163 nautical miles.


P
NORTH

Impact Structures

Impact structures are the records of the Earth's encounters with objects from space, chiefly asteroids and cometary nuclei. It has been estimated that there are about 1,000 asteroidlike objects in Earth-crossing orbits and nearly as many comets. On average, about three asteroids more than half a mile in diameter strike the Earth every million years and one asteroid larger than 6 miles in diameter strikes the Earth every 40 million years or so. Most of the impact structures in the conterminous United States are in the Coastal Plain or Interior Lowlands because these regions have remained stable for hundreds of millions of years; elsewhere, many impact features may have been removed by erosion, destroyed by tectonic processes, or covered by younger lava or sediments. The size of the crater produced by an impact is many times the diameter of the projectile. For example, the 15-mile-diameter Ries crater in Germany was probably produced by a projectile a mile or two in diameter. Seventeen known or strongly suspected impact structures (table 1) are recorded in the continental United States and adjacent parts of the continental shelf. These range in diameter from a few hundred feet (Haviland, Kans.) to about 60 miles (Chesapeake Bay, Va.) and in age from about 50,000 years (Meteor Crater, Ariz.; fig. 18) to about 360 million years (Flynn Creek, Tenn.). Only one, the Avak structure, has been recognized in Alaska.

Table 1. Impact structures in the United States.

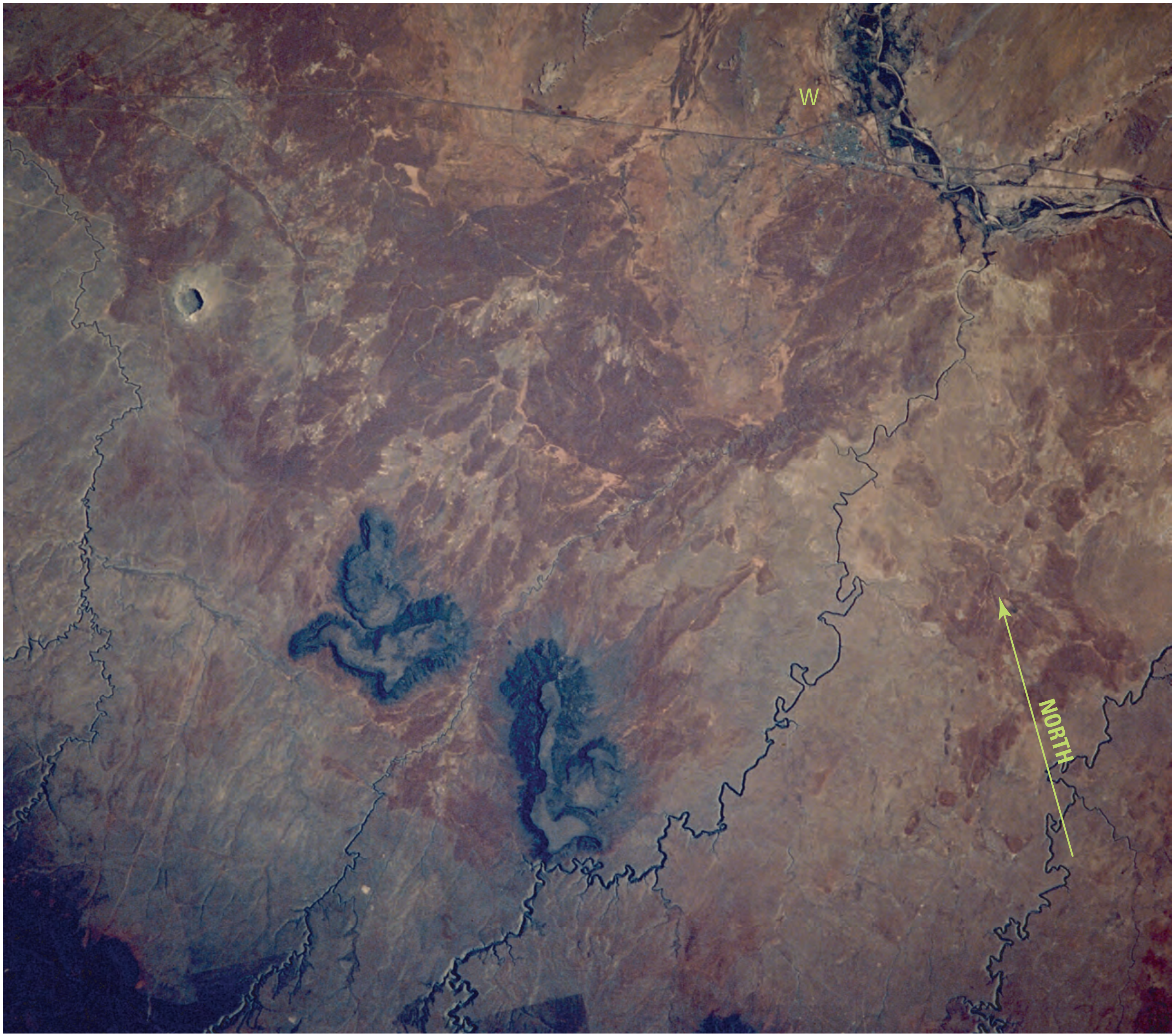
	Name	Lat	Long	Diameter (miles)	Age	Remarks
1.	Meteor Crater, Ariz.	35°02’	111°01’	0.3	50,000 years	Meteoric fragments identified.
2.	Odessa Craters, Tex.	31°45’	102°28’	.01	250,000 years	
3.	Haviland Crater, Kans.	37°35’	99°10’	.68	less than1 million years	
4.	Toms Canyon, beneath the ocean southeast of New Jersey	39°05’	72°50’	12.5	35 million years	Buried; found by drilling and geophysics; impact in ocean.
5.	Chesapeake Bay, Va.	37°16’	76°01’	60	35 million years	
6.	Bee Bluff, Tex.	29°02’	99°51’	1.5	less than 40 million years	Shock features identified.
7.	Hico, Tex.	32°00’	98°02’		less than 60 million years	
8.	Manson, Iowa	42°35’	94°31’	22	74 million years	Buried; found by drilling and geophysics.
9.	Sierra Madera, Tex.	30°36’	102°55’	8	100 million years	Shock features identified.
10.	Redwing Creek, N. Dak.	47°36’	103°33’	6	200 million years	
11.	Wells Creek, Tenn.	36°23’	87°40’	9	200±100 million years	
12.	Decaturville, Mo.	37°54’	92°43’	3.5	less than 300 million years	Shock features identified
13.	Kentland, Ind.	40°45’	87°24’	8	300 million years	
14.	Middlesboro, Ky.	36°37’	83°44’	3.5	300 million years	
15.	Serpent Mound, Ohio	39°02’	83°24’	4	300 million years	
16.	Crooked Creek, Mo.	37°50’	91°23’	3.5	320±80 million years	
17.	Flynn Creek, Tenn.	36°17’	85°40’	2.4	360±20 million years	
18.	Avak, Alaska	71°25’	156°63’	7.5	greater than 95 million years	Buried, found by drilling and geophysics.

[lat, latitude; long, longitude; ±, plus or minus]

Figure 18. Meteor Crater, Arizona. Meteor Crater is visible in the upper-left (northwestern) part of the photograph; it is about 4,000 feet in diameter and about 600 feet deep. It was produced by impact of a meteorite in the flat-lying sedimentary rocks of the Colorado Plateau about 50,000 years ago. The target rocks were sandstone, limestone, and dolomite of the Coconino, Toroweap, and Kaibab Formations of Permian (late Paleozoic) age and sandstone and siltstone of the Moenkopi Formation of Triassic (early Mesozoic) age. The Permian rocks appear light gray in the photograph, while the Triassic (Moenkopi) rocks appear reddish brown. The light-colored fringe around the crater is composed of material ejected during impact. East and West Sunset Mountains, the two dark hills visible in the lower part of the photograph, are underlain by young basalt flows. Because of its proximity to the San Francisco Peak volcanic field, Meteor Crater was originally thought to be a volcanic crater, but its impact origin is now well established. Calculations suggest that it could have been caused by an object 100 feet in diameter traveling at a speed of 9 miles per second. The force of the impact is estimated to have been equivalent to the explosion of 4 or 5 megatons of TNT.

Winslow, Ariz. (W) is visible near the upper-right corner of the photograph. The highway parallel to the upper edge is Interstate Highway 40. The meandering stream that flows north through Winslow is the Little Colorado River.

Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center; (photograph STS040-614-58; available from http://eol.jsc.nasa.gov). Direction of view is north; altitude is not given.


W
NORTH

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Glossary

accreted terrane A package of rocks that has arrived in its present position by plate-tectonic movements, either by subduction of intervening oceanic crust or by lateral movement along the margin of the continent.

alluvium A surficial deposit of silt, clay, sand, or gravel laid down by running water.

andesite A gray volcanic rock composed of subequal amounts of calcium and sodium-rich feldspar and dark iron- and magnesium-rich minerals, and minor amounts of quartz.

anorthosite A plutonic rock composed almost entirely of calcium-rich feldspar.

anticline A fold in which the rock layers have been bowed upward into an arch.

Archean In the stratigraphic time scale, the first eon of the Precambrian. It extended from about 3.8 billion to 2.5 billion years ago.

argillite A hard, massive sedimentary rock formed by compaction of clay and silt.

basalt A black or dark-gray volcanic rock composed of subequal amounts of calcium-rich feldspar and various dark iron- and magnesium-rich minerals and little or no quartz.

basement rocks A collective term for metamorphic and plutonic rocks that underlie sedimentary and volcanic rocks. In many cases it refers to Precambrian rocks that underlie Paleozoic and younger rocks in an area.

batholith A pluton that is exposed over an area of at least 40 square miles at the surface.

bedrock A general term for the rock, generally solid, that underlies soil or other unconsolidated material at the land surface.

blueschist A schistose metamorphic rock formed at very high pressure and moderate temperature that contains blue, sodium-rich minerals.

breccia A rock composed of a jumble of angular rock fragments cemented by finer grained materials. Breccia can be formed by sedimentary or volcanic processes or by faulting.

caldera A large, more or less circular depression formed by explosive volcanic eruptions.

Cenozoic The last eon of the stratigraphic time scale. It extends from about 65 million years ago to the present.

chert An extremely hard sedimentary rock made up of tiny interlocking crystals of silica (SiO_2). It may form by chemical precipitation of silica from sea water, by deposition by microscopic organisms, or by chemical replacement of limestone. It is also called flint.

collisional episode In plate tectonics, sometimes used to describe an event when two or more plates impinge on one another. The word "collision" is somewhat misleading because it implies a rapid encounter that involves momentum whereas plates are moving at only a few centimeters per year when they "collide."

complex An assemblage or mixture of rocks of different origins, commonly having complicated and obscure relations to one another.

conglomerate A sedimentary rock that contains abundant pebbles, cobbles, or boulders of various older rocks.

continental crust The type of Earth's crust that underlies continents. It is composed chiefly of granitic and intermediate plutonic rocks and metamorphic rocks. Continental crust is much thicker and lighter than oceanic crust, so it is rarely subducted when two tectonic plates collide.

convergent plate margin A boundary between tectonic plates along which one plate is being subducted beneath the other.

craton A large, stable area of continental crust, such as the interior of North America.

Cretaceous In the stratigraphic time scale, the last period of the Mesozoic Era. It lasted from about 144 to 65 million years ago.

delta An accumulation of sediment deposited where a stream or river enters a lake or the ocean. So named because most such accumulations have the shape of the Greek letter delta (Δ).

depositional age The time at which a sedimentary or volcanic rock was formed.

dip The inclination of a plane measured perpendicular to a horizontal line on the plane.

docking In plate tectonics, the joining together of tectonic plates or fragments of plates.

dolomite A mineral composed of calcium-magnesium carbonate ($CaMgCO_3$); also a sedimentary rock composed of the mineral dolomite.

downwarp A large, more or less circular depression in rock layers caused by subsidence.

eolian Pertaining to the wind. Commonly used to describe materials deposited by the wind, such as dune sand and loess.

evaporite A sedimentary rock composed of minerals deposited during evaporation of salty water, either sea water or lake water. The minerals include rock salt, gypsum, and various sulfate, borate, and nitrate minerals.

fault scarp An approximately linear break in the land surface caused by offset across a fault.

faulting The formation of approximately planar breaks in rocks along which rocks on one side are moved with respect to those on the other.

flysch A thick sequence of sedimentary rocks, chiefly shale, dark sandstone, and conglomerate deposited in a submarine basin in front of a rising mountain range.

folding The formation of approximately linear wrinkles in rock layers.

fore-arc basin An elongate basin that lies between the volcanic arc and the trench along the margin of a tectonic plate where a plate is being subducted beneath it at a convergent plate margin.

geologic age The time at which a rock formed or when some other geologic event occurred. Geologic ages are stated in years before the present (based on age determinations from decay of radioactive elements) or with reference to the stratigraphic time scale.

geophysical studies Studies of the physical properties of the Earth and its various layers. These include surveys of gravity, magnetism, and travel speeds of shock waves from earthquakes or explosions, all of which give clues to the density and composition of rocks in and beneath the crust.

gneiss A metamorphic rock characterized by layers or aligned streaks of mineral grains. Gneiss can be formed from sedimentary, volcanic, or plutonic rocks by intense metamorphism and deformation. Generally, most traces of features that allow identification of the rock from which it has been derived are obliterated during metamorphism.

granitic Said of light-colored plutonic rocks composed chiefly of quartz and feldspar and small amounts of mica, hornblende, and other minerals.

gravity anomaly The amount that the pull of gravity at the Earth's surface differs from the value predicted by a mathematical model based on a uniform Earth. Positive gravity anomalies indicate bodies of heavier than average rocks at depth; negative anomalies indicate lighter than average rocks.

growth fault A fault in sedimentary rocks that forms by slow creep of wet sediments down a slope at the same time they are being deposited. Such faults are common in the Gulf Coastal Plain.

intermediate Said of medium- to dark-gray plutonic or volcanic rocks composed of roughly equal amounts of quartz, feldspar, mica, and hornblende.

Jurassic In the stratigraphic time scale, the first period of the Mesozoic Era. It lasted from about 206 to 144 million years ago.

Laramide Formed during, or pertaining to, the Laramide orogeny.

limestone A sedimentary rock composed of calcium carbonate ($CaCO_3$) deposited by precipitation from sea or lake water or by the accumulation of shells and other parts of various aquatic organisms.

mafic Said of dark-colored plutonic or volcanic rocks composed chiefly of feldspar and dark minerals rich in iron and magnesium, such as hornblende, pyroxene, and olivine, and containing little or no quartz.

magnetic anomaly The amount by which the pull of the Earth's magnetic field measured at the surface or from aircraft or satellites differs from the value predicted by a mathematical model based on a uniform Earth. Positive anomalies indicate magnetic rocks in the upper part of the Earth's crust; negative anomalies indicate less magnetic rocks.

melange A mappable body of rock containing blocks of all sizes of a variety of rocks in a fine-grained matrix and characterized by lack of internal continuity. Melange is commonly formed in subduction zones where bodies of sedimentary rocks deposited along the leading edge of a plate are carried beneath the plate during subduction.

Mesozoic The era in the stratigraphic time scale that extended from about 248 to 65 million years ago.

metamorphic rock Rocks formed by recrystallization of mineral grains in older sedimentary, volcanic, or plutonic rocks during metamorphism.

metamorphism Change in the chemical composition, physical properties, and component minerals in a rock in response to changes in temperature, pressure, and (or) chemical conditions.

migmatite A rock made up of a mixture of metamorphic and plutonic rock. Migmatite forms either by partial melting of metamorphic rock at high temperatures or by injection of igneous material into the metamorphic rock.

Mississippian In the stratigraphic time scale, the period in the Paleozoic Era that lasted from about 354 to 323 million years ago.

moraine A mound, ridge, or other accumulation of glacial debris (till).

mudflow deposits A deposit laid down by flows of fine-grained, water-saturated material commonly carrying angular pieces of rock. When consolidated, these materials form one type of breccia.

Neogene In the stratigraphic time scale, the last major subdivision of the Tertiary Period. It lasted from about 24 to 1.8 million years ago. It includes the Miocene and Pliocene Epochs.

novaculite A very hard, even-textured, light-colored type of chert, commonly used as whetstone.

oceanic crust The type of Earth's crust that typically underlies ocean basins. Oceanic crust is made up largely of rocks having the composition of basalt and is much thinner and denser than continental crust, so that it is commonly subducted when two plates "collide."

oceanic plateau A region of abnormally thick oceanic crust formed by eruption of large volumes of basalt on older oceanic crust.

ophiolite Pieces of oceanic crust that have been carried up onto the leading edge of a plate during closure of an ocean. Ophiolites typically consist of basalt in pillowlike masses formed during eruption in deep water; closely spaced, nearly vertical sheets of basalt; and gabbro (a dark plutonic rock having the composition of basalt but coarser grained).

orogeny An episode of uplift and mountain building.

Paleogene The first major subdivision of the Tertiary Period in the stratigraphic time scale. It lasted from about 65 to 24 million years ago. It includes the Paleocene, Eocene, and Oligocene Epochs.

Paleozoic The era in the stratigraphic time scale that lasted from about 540 to 248 million years ago.

paleomagnetic measurement Measurement of the alignment of magnetic minerals in a rock. The magnetic grains become aligned with the magnetic field that existed at the time a sedimentary rock was deposited or a volcanic rock cooled. Such measurements allow us to estimate the latitude at which the rock formed and the amount it has since been rotated.

Pennsylvanian In the stratigraphic time scale, the period in the Paleozoic Era that lasted from about 323 to 290 million years ago.

Permian In the stratigraphic time scale, the last period in the Paleozoic Era. It lasted from about 290 to 248 million years ago.

phyllite A fine-grained, lustrous, mica-rich metamorphic rock formed from siltstone or shale at relatively low temperature and pressure. Schist is formed from the same rocks but at higher temperature and pressure.

plate tectonics The theory accepted by most earth scientists that the brittle outer parts of the Earth's crust and mantle are divided into a number of moving, semirigid plates and that the interaction of these plates drives many geologic phenomena, including mountain building, volcanoes, and earthquakes.

pluton A sizable body of generally coarse-grained igneous rock that has crystallized at depth below the Earth's surface

plutonic rocks Rocks formed by cooling and crystallization of molten igneous material at depth below the Earth's surface. Plutonic rocks are generally more coarsely crystalline than volcanic rocks.

Precambrian In the stratigraphic time scale, the interval of geologic time prior to the beginning of the Paleozoic Era. It lasted from the origin of the Earth (about 4.5 billion years ago) to about 540 million years ago.

Proterozoic In the stratigraphic time scale, the last eon in the Precambrian. It lasted from 2.5 billion years ago to the beginning of the Cambrian (the first period in the Paleozoic era) about 540 million years ago.

pyroclastic rock A rock formed of grains or blocks of material ejected from a volcanic vent.

Quaternary In the stratigraphic time scale, the last period of the Cenozoic Era. It began about 1.8 million years ago and extends to the present.

residual soils Soil produced by weathering of bedrock in place without significant movement of material.

rift An approximately linear zone of faulting formed where a tectonic plate is being pulled apart. In continental crust a rift is generally marked by a linear valley filled with young sediments and flanked by older rocks.

rhyolite A light-colored volcanic rock composed of sodium- and calcium-rich feldspar, quartz, and small amounts of dark minerals. Most rhyolite contains significant amounts of volcanic glass.

sandstone A sedimentary rock formed by the cementation of grains of sand. The cementing material is commonly silica, iron oxide, or calcium carbonate.

sea mount An undersea volcano.

sedimentary rocks Rocks composed of material derived from weathering or disintegration of older rocks that was transported and deposited by water, air, or ice, or of material that accumulates by other natural agents, such as chemical precipitation from solution or secretion by organisms. Sedimentary rocks are generally deposited in more or less continuous layers.

sequence An informal name for a group of related sedimentary rock layers.

shale A fine-grained sedimentary rock formed by consolidation of clay, silt, or mud. It generally has a finely laminated structure that causes it to break into thin chips or plates.

siltstone A fine-grained sedimentary rock formed by consolidation of silt. Siltstone generally lacks the laminated structure of shale and tends to break into small angular blocks.

strata A collective term for layered sedimentary rocks.

stratigraphic time scale A time scale established from the study of sedimentary rock layers and based on the physical relations of the layers to one another and on the fossils they contain. Stratigraphic ages of igneous and metamorphic rocks are determined by their relations to sedimentary rocks that have been placed in the stratigraphic time scale <http://ngmdb.usgs.gov/Geolex/geolex_home.html>. Note that when we describe the age of a sequence of sedimentary layers we describe them as "lower," "middle," or "upper," because that is the order in which they were deposited, but when we describe intervals of time we describe them as "early," "middle," or "late." Thus, Upper Cambrian rocks were deposited during Late Cambrian time.

strike-slip fault A fault along which the movement of one side with respect to the other is horizontal. Strike-slip faults are described as "right-lateral" or "left-lateral" depending on whether the side opposite you moves to your right or your left as you stand facing the fault.

subduction The process by which one tectonic plate sinks beneath another plate as the two approach one another.

subduction zone The zone along a plate boundary where subduction is taking place.

surficial deposits Unconsolidated materials that lie at or near the land surface. The term includes soil, stream, glacial, and lake deposits, and windblown materials.

suture A line or zone along which two tectonic plates have joined together.

syncline A fold in which rock layers have been bent downward into a trough.

tectonic plate One of the large segments of the Earth's crust that is moving in relation to other parts of the crust. The plates may be made up of continental crust or oceanic crust, or partly of each.

terrane A fault-bounded body of rock of regional extent that has a geologic history distinctly different from the adjoining rocks. Not to be confused with "terrain," which refers to the physical features of the land surface.

Tertiary In the stratigraphic time scale, the first period of the Cenozoic Era. It lasted from about 65 to 1.8 million years ago.

thrust fault A flat or gently inclined fault along which the rocks above have moved relative to the rocks below. Thrust faults are generally formed by compression.

till Material deposited by or beneath glacial ice. It generally consists of unstratified clay, silt, and sand studded with pebbles, cobbles, and boulders having a wide variety of sizes and shapes.

Triassic In the stratigraphic time scale, the first period in the Mesozoic Era. It lasted from about 248 to 206 million years ago.

tuff A consolidated deposit of volcanic ash and larger fragments explosively ejected from a volcano.

volcanic arc An arcuate chain of volcanoes formed along the leading edge of a tectonic plate as another plate is subducted beneath it. Where the plate collision takes place beneath the ocean the volcanoes commonly form a chain of islands commonly described as an island arc. The Aleutian Islands are an example.

volcanic ash Fine material explosively ejected during a volcanic eruption. It is generally composed of tiny shards of volcanic glass.

volcanic breccia A rock composed of relatively large, angular fragments of volcanic rock embedded in finer grained volcanic material. Such breccias are formed either from materials ejected directly from a volcanic vent, or from mudflows generated by heavy rains, or by meltwater from snowfields or glaciers suddenly heated by volcanic eruptions.

volcanic rocks Finely crystalline or glassy igneous rocks that form by volcanic action at or near the surface. They are composed of material that has either been ejected explosively or that flowed out onto the surface as lava.

welded tuff A tuff deposit composed chiefly of fragments of volcanic glass that were erupted at such a high temperature that they welded together when they came to rest to form a dense volcanic rock. Most welded tuff has the composition of rhyolite or closely related rocks.

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