

PART I

THE GROUND OF UTAH MINING



# GEOLOGY AND UTAH'S MINERAL TREASURES

*William T. Parry*

## INTRODUCTION

The occurrence of valuable mineral resources in Utah and the West is not accidental, but rather the result of understandable geological processes. However, the original discoverers did not understand these processes. Copper is at Bingham, coal at Price, and uranium at Moab because of the geological histories of these areas. A search for coal at Bingham or copper in Carbon County would be, and probably was, futile. Not only did the discoverers not understand the diverse processes, but neither did the scientists of the day. Much of what we know has been learned in the past few decades. The geological events that shaped present-day Utah formed the host rocks that contain the minerals and initiated the processes that formed the diverse assemblage of deposits that are Utah's mineral heritage. The geologic history of mineral resources is long and complex.<sup>1</sup>

This essay examines the geology of mining in Utah. The first section describes the general theoretical background. The second outlines the geological development of the West. And the third part explores the geology of each of the regions covered in the other chapters in this book.

## GEOLOGIC TIME

The range of geologic time involved exceeds by many orders of magnitude any time span with which we are familiar. We need some way to deal with the enormity of time involved in the events that shaped Utah's geology. One approach is to divide geologic time into successively smaller units, each with its own name, so that we can refer to them without the number of years getting in the way. Next, because of the technological discovery of radioactive age dating, we can specify the age and duration of each of the named units in millions of years. The named age blocks, together

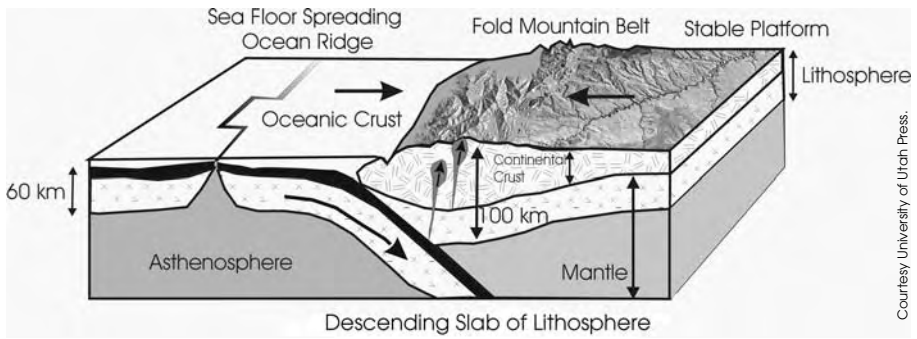


Figure 1. Schematic diagram of a plate tectonic system. Here a continental plate moving to the left converges with an oceanic plate moving to the right in response to formation of new oceanic lithosphere at a mid ocean ridge. The oceanic lithosphere is more dense than continental lithosphere and sinks downward. As it does so, the increased temperature, pressure, and changing chemical environment cause melting to occur. The melted rocks are buoyant and rise toward the surface. The convergent continental margin forms a fold mountain belt. All photographs and drawings in this chapter are by the chapter author.

with their absolute ages and durations in millions of years, appear in table 1 (see page 10). The table also includes the specific geologic event important to Utah's mineral resources that is associated with each block of time.

### *Plate Tectonics*

The geological story of Utah is a journey through time and around the globe, for the geological architecture of Utah is not only ancient, but also much of it developed in distant locations. How is this all possible? Explaining the sequence of events that have shaped the geological architecture of Utah relies on the theory of plate tectonics. This theory holds that the outer, rigid layer of the Earth is divided into a series of separate plates and that these plates are free to move about the surface of the Earth in response to driving forces from within. The energy that drives the motion is heat; the Earth is a giant heat engine. Movement of the plates results in separation or divergence of some plates such as the divergence that produced the opening of the Atlantic Ocean. Plates may also converge and collide such as the impact that produced the spectacular Himalayas and closed the ocean that had separated India from Asia. This type of convergence is shown schematically in figure 1. Some plates may also slip past adjacent plates such as in the case of the San Andreas Fault in California.

As a consequence of convergence, oceans disappear and continents collide, producing spectacular mountain ranges. Interaction of crustal plates produced Utah's mountains, volcanoes, and mineral deposits. Geologists have known for nearly a century that vertical movements of the earth's crust were common. Thus, shells of marine snails, clams, and other sea creatures are found in rocks well above sea level.

Only during the last few decades, however, have scientists discovered that horizontal motions were just as common as vertical ones. Horizontal movements and the resulting plate interactions produced many of the features of present-day Utah.

To understand the lateral movement of continents and the consequences for Utah, we must review some geological theory. First, the earth is layered concentrically. The surface layer is the crust, then comes the mantle, and then the core. The crust and uppermost mantle form a rigid layer with a soft layer immediately underneath. It is this rigid layer of crust and mantle, called the *lithosphere*, that moves. The rigid layer consists of separate plates, and accommodating motion of one plate with respect to another on the spherical earth requires some plate boundaries to converge and others to diverge. Modern tools such as global positioning satellites confirm the direction and magnitude of plate motions.

### GEOLOGICAL AND MOUNTAIN-BUILDING HISTORY

#### *Precambrian (4,600 to 570 million years ago)*

Now we are ready for the journey that accounts for the geological features of the region encompassed by Utah. We begin with the basement, the foundation on which the younger rocks are placed. Horizontal motion of plates has fragmented continents and reassembled others. North America is composed of a number of fragments of ancient continents that have been welded or sutured together by plates converging at various periods in geologic history. The ancient basement rock of Utah is the assemblage of at least two continental fragments called *cratons* (Greek for “shield”). In this region, two separate continental masses of different age were sutured together near central Utah. Following accretion or addition of largely volcanic rocks to the southern margin of what was to become North America 1.8 to 1.4 billion years ago, the Utah region was mountainous and had been eroding for many millions of years, producing raw material for a new generation of rocks. At that time the ocean shoreline (now west, but the orientation of the continent was different than today), lay at about the present-day location of Elko, Nevada. On the north was the ancient Wyoming craton with rock ages in excess of 2.5 billion years, possibly as old as 3.5 billion years, and on the south was the Arizona craton, largely volcanic in nature, which collided with and was sutured to Wyoming about 1.6 to 1.8 billion years ago in a mountain-building event.

The ocean basin that separated these two lithospheric plates gradually disappeared as they approached one another. The continents finally collided, forming a suture zone that trends from Cheyenne, Wyoming, through the Uinta Mountains and west across the Oquirrh Mountains to the Deep Creek Mountains on Utah's western border. The collision resulted in the formation of a mountain range that has long since eroded away; only roots and volcanic rocks remain. This ancient suture zone marks the locus of present mineral deposits in overlying younger rocks at Park

## Kinds of Faults

There are basically three kinds of faults: a normal fault shown in figure 2A; a thrust fault, like the one shown in figure 2B; and a strike-slip fault. Mineral deposits in Utah are often associated with normal or thrust faults. The present landscape is reflective of normal faults. Utah has two systems of great faults. The first system is the oldest and is the result of compressive forces directed from the west during an episode of lithospheric plate convergence. The North American lithospheric plate moving west converged with an oceanic plate.

Utah's great thrust faults—the Charleston-Nebo, the Willard-Paris, and other related thrust faults shown in figure 3—have their beginning in Cretaceous time. These faults are exposed to view due to the large displacements on normal faults that bound the mountain blocks such as the Wasatch. In the Pahvant Mountains and nearby Canyon Range and in the Wasatch, we see rocks as old as Precambrian thrust over much younger rocks such as Paleozoic and Mesozoic sedimentary rocks. Crustal shortening can amount to as much as 100 miles or more on these faults. Compressive forces from converging lithospheric plates produce thrust faults and folds. Anticline and syncline folds are shown in figure 4.

The second system of faults are normal. These normal faults resulted from extension of the region to the west. The major normal faults that affect the present landscape are the Wasatch Fault in northern Utah and the Sevier and Hurricane Faults in southern Utah and northern Arizona shown in figure 3. Each of these faults is generally down to the west. Normal faults also bound each of the mountain ranges in the Great Basin west of the Wasatch.

The normal faults are younger than the thrust faults. They have their beginning in Tertiary time and are no older than 35 million years or so. Historical earthquake activity in Utah indicates that displacement is still taking place on some of these normal faults and that the Great Basin is still growing wider. The Wasatch Fault in northern Utah is the longest. Total displacements on the faults can be established by observing offset formations on their hanging and footwall sides. The Hurricane Fault has a displacement of 8,000 feet. When hanging-wall rocks are covered by valley fill, such as with the Wasatch Fault, displacements can be estimated by reconstructing material removed from the footwall by erosion. The Wasatch Fault probably has a displacement of at least 30,000 feet.



Courtesy University of Utah Press.

Figure 2a. Normal Fault

Figure 2. Kinds of faults. First a normal fault example from the Moab fault at Bartlett Wash in southeastern Utah. Here, the Cretaceous age Cedar Mountain formation on the right has been faulted down with respect to the older Jurassic age Entrada sandstone on the left. Next, a thrust fault example from the Alta thrust fault in the Wasatch Mountains. Here the Early Paleozoic Tintic Quartzite above has been thrust over the younger Mississippian limestone beneath. Note, the view has been rotated to remove the uplift on the Wasatch fault.



Courtesy University of Utah Press.

Figure 2b. Thrust Fault

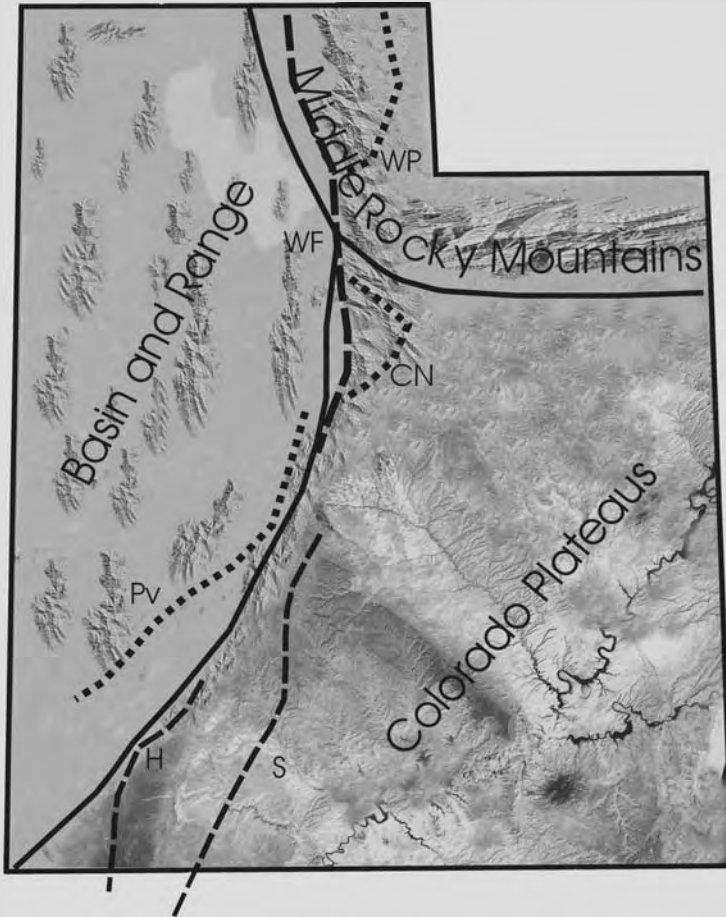
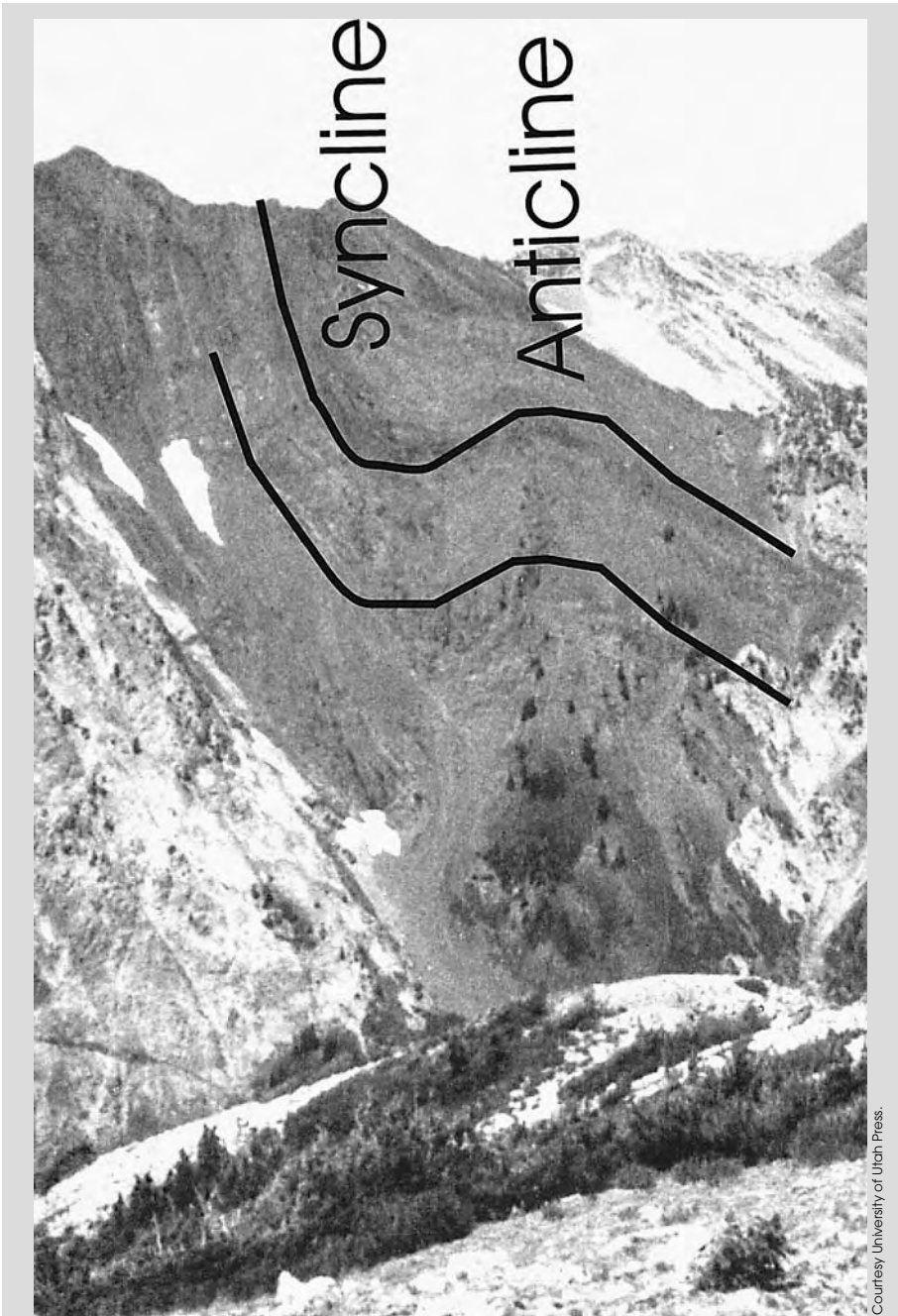


Figure 3. Faults and physiography of Utah showing each of the physiographic provinces and examples of the major normal and thrust faults. Dotted lines represent thrust faults and dashed lines are normal faults. WP is the Willard-Paris thrust fault, CN is the Charleston-Nebo thrust fault, PV is the Pahvant thrust fault, WF is the Wasatch normal fault, S is the Sevier normal fault, and H is the Hurricane normal fault.

### Utah's Triple Personality

Examination of the geologic and physiographic map of Utah shown in Figure 3 shows three major characters to the state. First, the western half appears somewhat like the wrinkled skin on drying fruit with its north-south trending mountain ranges and intervening basins. This part of Utah is known as the Basin and Range Province. Second, the smoother topography in the southeastern portion of the state is known as the Plateaus province. Third, the rugged mountains that make the central spine of Utah together with the craggy peaks of the Uinta Mountains make up the Rocky Mountains province. Each of these regions has characteristic geology.



Courtesy University of Utah Press.

Figure 4. Kinds of folds. The compressive forces from converging lithospheric plates produces thrust faults and folds. An example of an anticline and a syncline shown here from the Precambrian Big Cottonwood formation in Little Cottonwood Canyon.

TABLE I  
GEOLOGICAL AGES AND EVENTS IN UTAH

Age Millions of Years	Era	Period	Epoch	Event	Resource
		Quaternary	Holocene Pleistocene		Great Salt Lake
	Cenozoic				
66.4-1.6		Tertiary		Laramide	Bingham copper, lead, and zinc ore
144-66.4		Cretaceous		Sevier	Coal
208-144	Mesozoic	Jurassic		Nevadan	Morrison formation uranium host
245-208		Triassic			Chinle formation uranium host
					Homestake formation host for iron ore at Cedar City
					Host for silver at Silver Reef
					Thaynes host for silver at Park City
286-245		Permian		Sonoma	
320-286		Pennsylvanian			Limestone host for lead, zinc, and silver at Bingham
360-320		Mississippian			Great Blue limestone gold host at Mercur
					Humbug, Deseret, and Great Blue host for ore at Park City
408-360	Paleozoic	Devonian		Antler	
438-408		Silurian			Bluebell dolomite host for ore at Tintic
505-438		Ordovician			
570-505		Cambrian			
2500-570	Precambrian	Proterozoic		Accretion of Arizona to Wyoming	Middle Ophir limestone, copper, lead, zinc, silver host at Tintic and Wasatch Mountains Basement control on Wasatch Igneous trend
4600-2500		Archean			

City, Bingham, and Gold Hill. Evidently the suture had an effect on later geological processes.

Assembly of continental plates resulted in the formation of large supercontinents. One of these, formed long ago and far away, had formed by 750 million years ago in the Southern Hemisphere. This distant land is called Rodinia. Rodinia included North America nestled against eastern Antarctica.

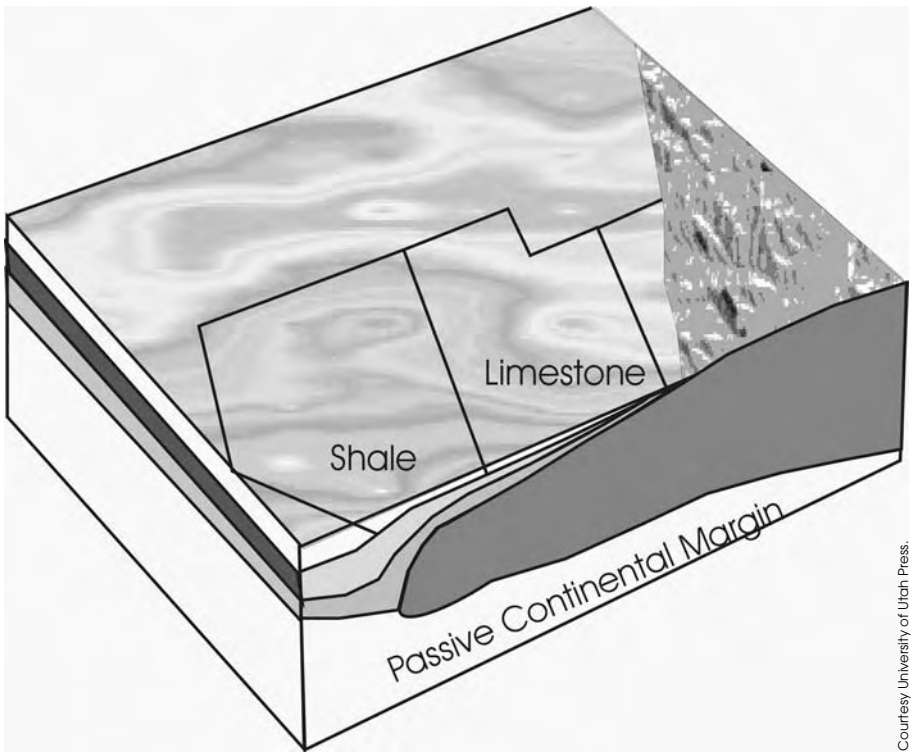
The Grouse Creek, Raft River, and Albion ranges in northwestern Utah expose Archean rocks 2,500 million years old. The Farmington Canyon complex in the Wasatch Mountains east of Farmington is Archean in age, exposed there due to displacement on the Wasatch Fault. The Red Creek quartzite in the eastern Uinta Mountains is also probably of Archean age. These old rocks represent the eroded roots of an ancient mountain range.

Beginning about 1.1 billion years ago, the edge of the continent was split in a great east-west rift where astonishing thicknesses of shale and sand accumulated, rocks that are now exposed in the Uinta Mountains and Big Cottonwood Canyon in the Wasatch Mountains. These sediments were exposed to the action of tidewater glaciers and are in places covered with deposits left by melting ice. A veneer of additional sandstone and shale covers these glacial deposits. Proterozoic sedimentary rocks 2,500 to 570 million years old, mostly only weakly metamorphosed, include the Uinta Mountain group and the Big Cottonwood series that overlie this ancient basement rock.

### *Paleozoic (570 to 245 million years ago)*

Rodinia broke apart, and fragments drifted in various directions across the globe. North America set off on a journey north, and by 530 million years ago, the western coast was near the equator. Salt Lake City is presently 700 miles from the Pacific Ocean, but earlier history places Utah much nearer the ocean and at times under water. Land areas of western Nevada and California were added to the North American continent much later. The northern margin of North America, which was to become its western part, was a broad, shallow, warm sea similar to the Coral Sea and the coast of northeastern Australia. The floor of the sea had numerous coral-building organisms living on it.

From 570 to 360 million years ago, an uneventful accumulation of sedimentary rocks formed in Utah and across Nevada, shown in figure 5. Sediments are thickest and most complete in western Utah. The sedimentary layers thin eastward and are sometimes even absent approaching the central portion of the continent. A great sandstone beach marched across Utah and the West, forming the first sedimentary deposits of the Paleozoic era. Sands and carbonate rocks, now exposed in the Grand Canyon, accumulated on a broad continental shelf in a tropical ocean near the equator that extended into Nevada and south into Arizona. These early Paleozoic rocks in Utah are mostly carbonate (limestone and dolomite) with lesser amounts of sandstone, quartzite, shale, and conglomerate. Sandstone and quartzite formed near shore on a passive continental margin. The belt of sandstone shifted east



Courtesy University of Utah Press.

Figure 5. Early Paleozoic western North America. The western continental margin was passive, not converging with the adjacent oceanic lithosphere. Quiet accumulation beach sand, limestone near the shoreline and shale in deeper water characterizes this period of time.

with the shoreline. Shallow-water offshore deposits consist of shales that contain one important limestone: the Middle Ophir. Farther from shore in deeper waters of the continental shelf, limestone deposits precipitated from seawater with the aid of biologic activity. Deepwater shales accumulated in central and western Nevada. Though quiet accumulation of sedimentary rocks on the continental shelf may seem uninteresting, these rocks had important consequences for Utah's mineral deposits, for they are the host rocks for the rich copper, lead, zinc, silver, and gold deposits in the Park City, Tintic, Big Cottonwood-American Fork, and other mining districts in Utah.

This period of quiet accumulation of sedimentary rocks came to a close with the beginning of an eventful mountain-building history that shaped Utah geology for the next 300 million years up until about 50 million years ago. The western edge of the continent became the focus of mountain-building events as the Antler Mountains formed a north-south chain near the continental margin near Elko, marking the growth of the continent into western Nevada. Erosion from these mountains provided debris for the ocean basin to the east in western Utah. Deposition of marine

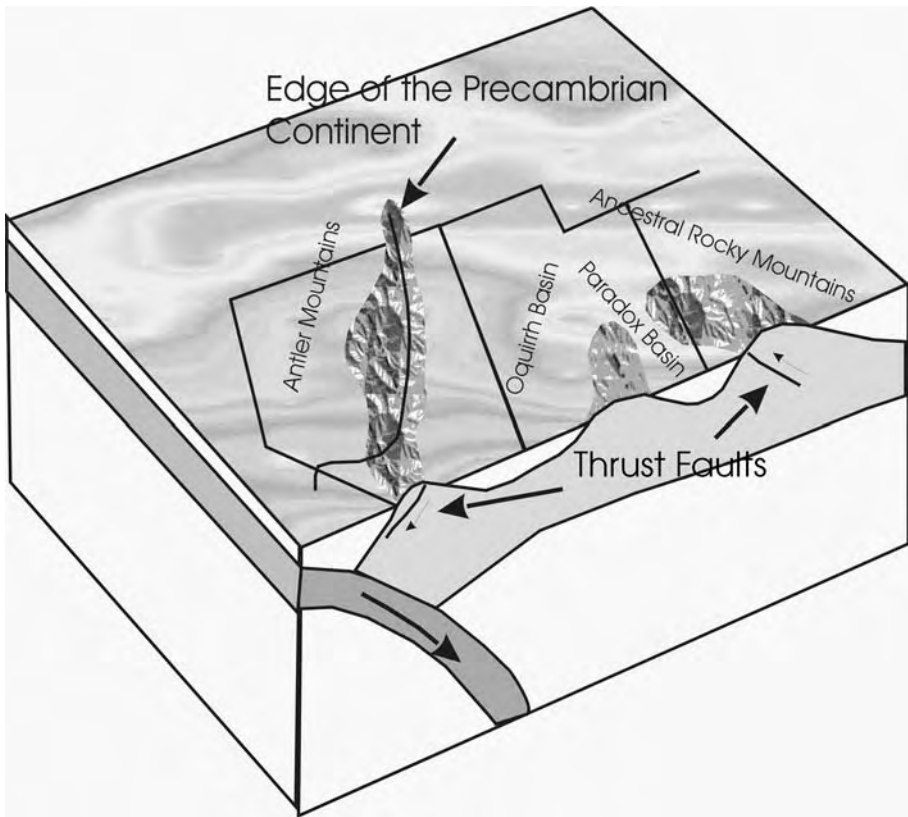


Figure 6. By Pennsylvanian time shown in this figure, the Antler mountains had formed in Nevada, the Ancestral Rocky mountains had formed in Colorado, and the Paradox and Oquirrh basins had formed in Utah.

carbonate, sandstone, and shale continued in a more restricted marine basin between the Antler highland and the continent.

Fragments of Rodinia continued to drift about on the globe until about 320 million years ago when the supercontinent of Pangea assembled. Assembly of Pangea was accompanied by collisions of continents and more mountain building. Next in the sequence of mountain-building events came a series of mountains in Colorado and adjacent southeastern Utah that occupied the present location of the Rocky Mountains and are thus called the Ancestral Rockies. These mountains formed when South America collided with North America in the Gulf of Mexico region. Accompanying the formation of the Utah portion of the Ancestral Rockies, two deep, fault-bounded marine basins formed, shown in figure 6. The first—in southeastern Utah near the present Green, Colorado, and San Juan Rivers—is called the Paradox Basin. Erosion from these mountains helped fill this basin. Because access to the open ocean was restricted and the climate may have been arid, much seawater evaporated, leaving behind thick accumulations of salt and related minerals. The physical properties

## Definitions of Rock Types

**Igneous rocks:** rocks that have been melted within the earth and have been emplaced in the subsurface or on the surface and solidified as they cooled.

**Sedimentary rocks:** rocks that are deposited by water, either running water in rivers or quiet water in oceans and lakes. Limestone is chemically precipitated from the water, sandstone, shale, and conglomerate are transported as particles.

**Metamorphic rocks:** rocks that have been transformed by heat and pressure.

**Crystalline Basement:** ancient igneous and metamorphic rocks upon which younger sediments are deposited.

of the salt (low density and plastic deformation) led to later salt-intrusion anticlines and faulting in southeastern Utah.

The name “Paradox” comes from much later geological processes that resulted from movement of salt that had accumulated in the Basin. The movement produced great northwest-to-southeast trending anticlines that collapsed as the salt dissolved and was removed forming valleys such as the valley where Moab is located. The Colorado River paradoxically flows directly across the north end of Moab Valley, and the Dolores River cuts Paradox Valley in Colorado at nearly right angles. The mountains formed near the Utah/Colorado border are now called the Uncompahgre Plateau, a northwest-to-southeast-trending mountain range with crystalline roots.

The second basin, formed in northwestern Utah and known as the Oquirrh Basin after the mountain range west of Salt Lake City, is composed largely of sediment that accumulated. The Oquirrh Basin accumulated an enormous thickness of sediment with a cyclic repetition of limestone, sandstone, and shale possibly because of sea-level fluctuation related to glacier advances and retreats. More than three miles of these sediments accumulated in water depths that sometimes exceeded 1,000 feet. The lower 4,000 feet of these sediments are now exposed on Mount Timpanogos.

Sediments in these two basins had important consequences for Utah’s mineral resources. In the Paradox Basin, both salt and potash accumulated along with much organic matter that later became petroleum. In the Oquirrh Basin, the limestones became a favorable host for the rich lead and zinc deposits in the Bingham Mining District.

With the Antler and nearby mountains to the west and the Ancestral Rockies to the east, most of Utah was still under water from 286 to 245 million years ago except for its southeastern corner. More mountains and terrain were added to western Nevada with the Sonoma mountain-building event. Sedimentary rocks that accumulated in the shallow ocean included sandstones, shales, and limestones. The Paradox Basin was completely filled with sediment, and wind-blown sand dunes covered the area. Deposition of carbonate and sandstone continued in the Oquirrh Basin

## GEOLOGY AND UTAH'S MINERAL TREASURES

of northwestern Utah. The limestones became the economically important host for rich silver-lead ores at Park City, Milford, and the Deer Trail Mine near Marysvale and an important source of phosphate mined on the flanks of the Uinta Mountains and tar sands located in Wayne and Garfield Counties. The limestone also formed a prominent rimrock of the Grand Canyon. The top of these sediments is an erosion surface that represents an interval of more than 5 million years before deposition of any younger sediment.

The Golconda thrust fault and accretion of associated Sonomia in a mountain-building event closed the Permian and ushered in the next major episode in Utah geology. For 325 million years, Utah had escaped the direct effects of mountain building. Episodes had produced mountains in Nevada and Colorado and sedimentary basins in Utah, but only the tip of the Ancestral Rockies had penetrated Utah. The Mesozoic era saw Utah pummeled by major mountain-building events.

### *Mesozoic (245 to 66.4 million years ago)*

The Mesozoic history of Utah includes several mountain-building events that changed the course of rivers and the location of oceans. The shoreline of the Pacific Ocean curved into Utah during the early Triassic, and much of the state was under water, once again separating Utah from the Sonoma and Antler Mountains in Nevada. A shelving lowland rose gently toward the Ancestral Rockies in eastern Utah. Sediments thickened from eastern Utah near the Ancestral Rockies west toward Nevada. The Woodside shale and Thaynes formations of the Wasatch Mountains were deposited at this time along with the Moenkopi formation of southern Utah.

Exposed rocks were then eroded for more than 10 million years. A large river flowed from the Ancestral Rockies west to the sea somewhat like the Nile River now flows into the Mediterranean, and, like the Nile, this ancient river crossed fields of sand dunes. That river transported floating logs that are now preserved in the Petrified Forest in Arizona. The river began in Colorado's Ancestral Rockies. River channels were filled with sands and gravels that became important sites for uranium mineralization in southeastern Utah and adjacent states.

Late Triassic sediments accumulated between Sonomia and the remnant Ancestral Rockies. Many of these Triassic rocks are red. Late Triassic and early Jurassic rocks included wind-deposited sand, forming the impressive sandstones of the Wingate, Navajo, and Entrada formations. Middle Jurassic rocks were deposited in a narrow marine belt in central Utah in front of the Nevadan mountain belt forming in eastern Nevada and western Utah. Late Jurassic sediments included the conglomerates and stream deposits of the Morrison formation deposited by east-flowing streams arising in the Jurassic mountains in eastern Nevada and western Utah. Igneous intrusions in western Utah are also Jurassic.

Pangea followed the fate of supercontinents such as Rodinia. Pangea began to break up with the opening of the South Atlantic Ocean. South America separated from Africa, and the western margin of South America pushed against the Pacific Ocean plate, beginning the formation of the Andes Mountains. North America

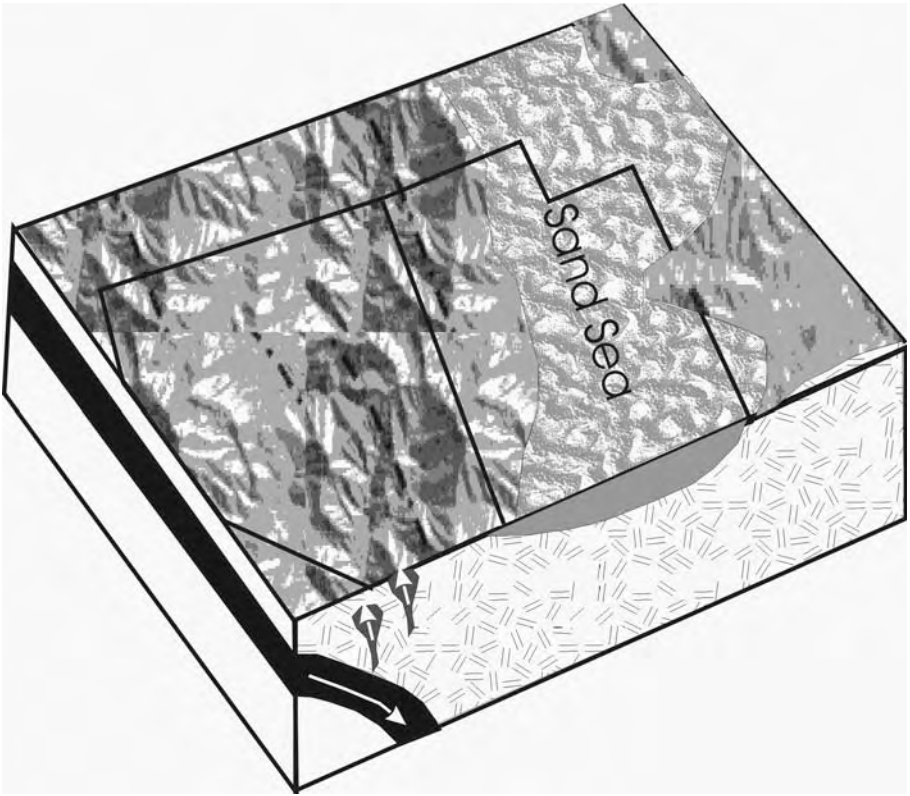


Figure 7. Utah in early Jurassic time was mostly covered by wind blown sand, one of the largest sand seas in the world. To the west were mountains formed by convergence of North America and the oceanic plate to the west. This convergence produced igneous rocks that are located in western Utah and Nevada.

separated from Europe as the North Atlantic Ocean opened, and North America collided with the Pacific plate, initiating the start of an Andean-type mountain range in Utah and Nevada. The volcanic activity associated with these events was first offshore, and the rivers followed westerly courses into the ocean.

North America continued to evolve with the opening of the North Atlantic Ocean and convergence of North America with the Pacific plate. The Andean-type mountain range continued to rise, causing a reversal in the drainages so that rivers flowed to the east from the mountain highland into a large sea that had developed connecting the Gulf of Mexico with the Arctic. The region was still a desert located about 15 degrees north of the equator with sand dunes similar to the Sahara today. The windblown sand accumulated in sedimentary formations that are widely distributed in Utah and adjacent states and spectacularly exposed in the cliffs of Zion Canyon in southern Utah today (figures 7, 8).

Continued convergence of North America with the Pacific plate and the attendant horizontal compressive forces and volcanic activity formed a very impressive



Figure 8. View of Zion Canyon from the East Rim Overlook looking southwards down the Virgin River. The cliffs are composed of Navajo sandstone, a rock that formed from accumulated wind-blown sand.

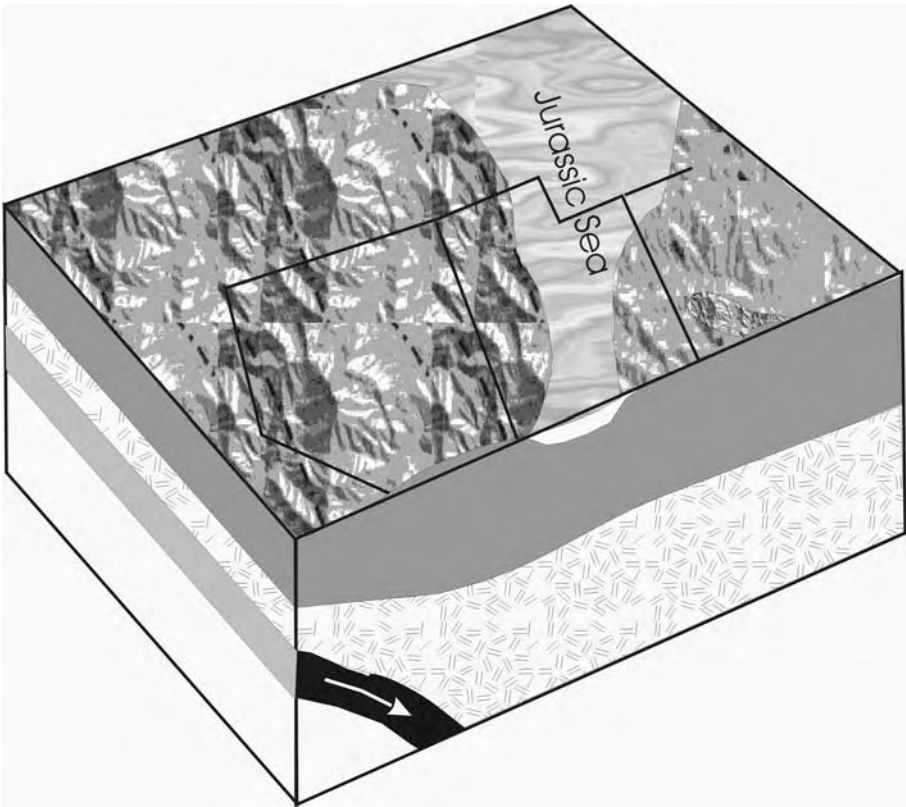
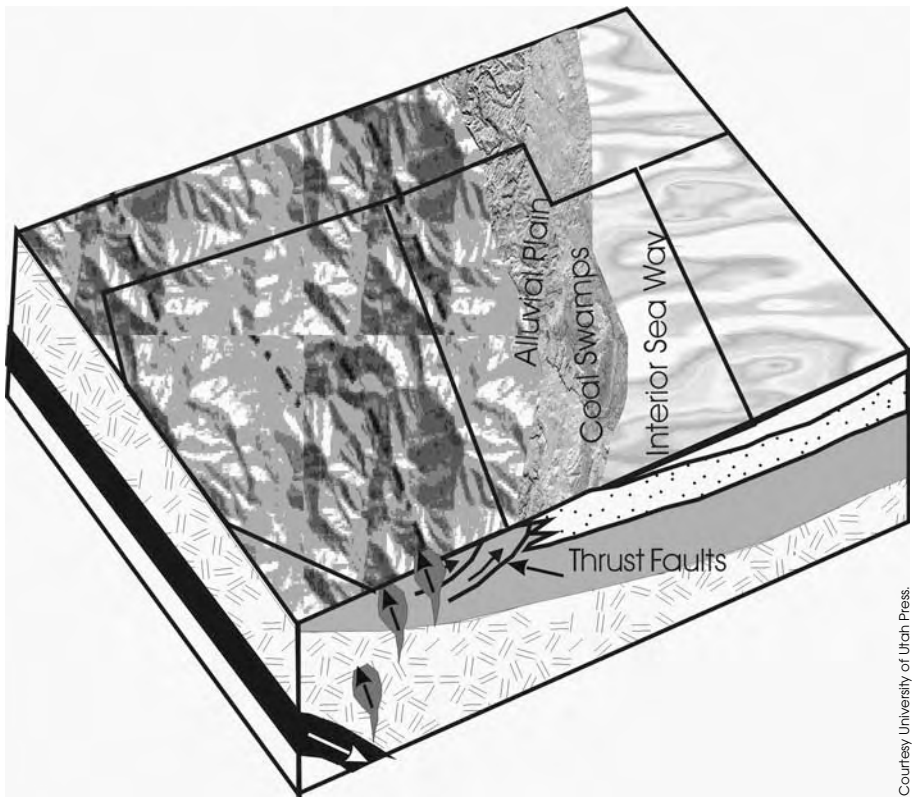


Figure 9. Utah in Mid Jurassic time with an arm of the ocean in central Utah where evaporation produced the salt deposits at Redmond and the gypsum that is mined at Nephi and Sigurd.

mountain range to the west, and streams continued to flow into the interior seaway. The horizontal compressive forces formed thrust faults, shortened the region, and thickened the crust. Rocks that had been deposited in the Oquirrh Basin, for example, were pushed tens of miles east. The rocks on Mount Timpanogos were among those thrust east, and the thrust fault lies in the subsurface beneath the mountain.

Utah, or at least western Utah, was very much like the Altiplano in southern Bolivia and northern Argentina. Dinosaurs roamed the stream floodplains and shorelines.

Continued mountain building in California and Nevada began to affect Utah more strongly so that west-flowing streams were interrupted by highlands that were forming and rivers were obliged to reverse their flow to the east. These mountain-building events continued to add terrain to North America. In fact, much of western Nevada and California became part of North America at this time. These mountain-building events produced some topographic changes in Utah. At times portions of the state were covered by a narrow arm of the ocean that invaded through Canada (figure



Courtesy University of Utah Press.

Figure 10. Continued convergence of western North America with the oceanic plate to the west resulted in subsidence from eastern Utah into Colorado and the formation of an interior sea that extended from about the Gulf of Mexico to the Gulf of Alaska. The alluvial plain and coastal areas were swampy and accumulated plant debris that was to become the coal deposits of Utah.

9). Evaporation of seawater left behind the salt and gypsum deposits in central Utah at Sigurd and Redmond. Marine limestone (Homestake member of the Carmel) is host to Iron County iron ores. Sediments from east-flowing rivers and large lakes covered these marine deposits. Abundant dinosaur remains are preserved in the rivers' channels.

The first igneous intrusions in Utah in more than 1 billion years formed in western Utah, and volcanic activity to the west deposited ash layers in Utah sediments. East-flowing streams continued to build deposits while mountain building and associated volcanic activity supplied the region with ash.

Cretaceous marine and nonmarine sediments were deposited to the east of the Sevier Mountain belt in western Utah as the area to the west rose and that to the east sank. Cretaceous coal deposits formed near the shoreline of the seaway shown in figure 10. At the end of the Cretaceous, eastern Utah was occupied by shifting river systems, swamps, and alluvial plains. Thick conglomerates were deposited at the foot of the Sevier Mountains in the west.

*Cenozoic (66.4 to 0 million years ago)*

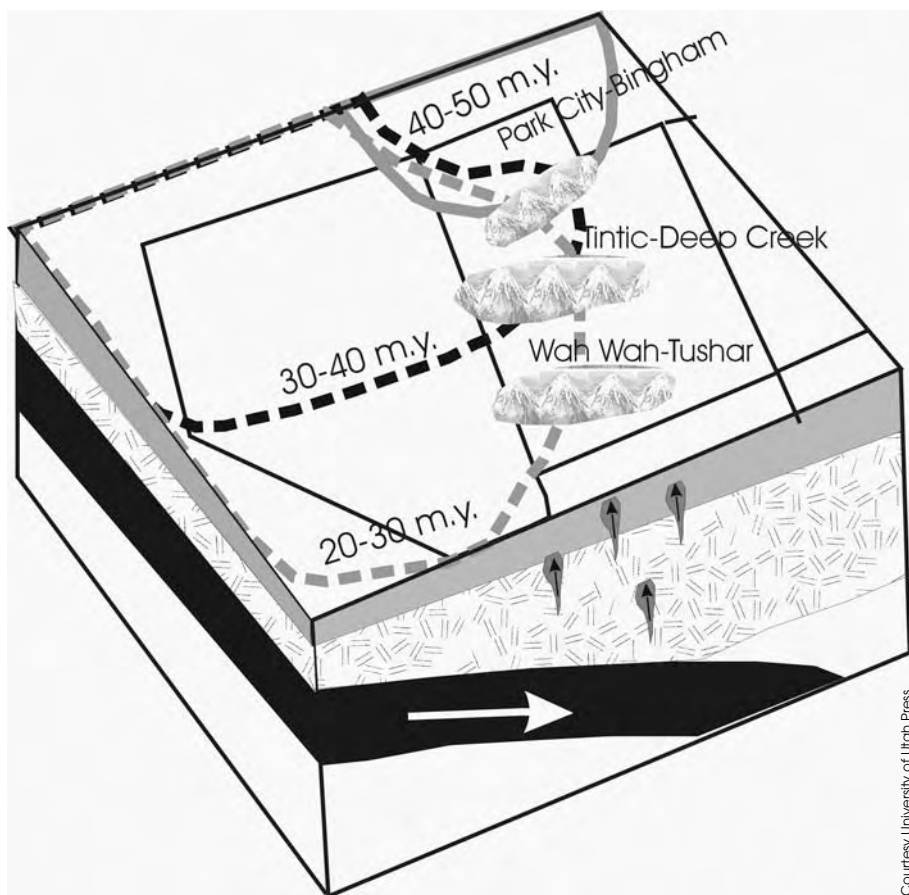
The Cenozoic era from 65 million years ago to the present consists of two geologic periods: the Tertiary and the Quaternary. During the Cenozoic, the present landscape developed, and many of the metallic ore deposits of Utah were formed. Events in the Tertiary period led to the growth of the Uinta Mountains, uplift of the San Rafael Swell, and formation of the rich petroleum deposits in the Uinta Basin and elsewhere. Continued uplift finally obliterated the interior seaway, causing the last vestiges of the ocean to disappear. With no ocean to drain the east-flowing rivers, lakes began to form. These lakes held predominantly fresh water where abundant tropical plants and animals were preserved as fossils. The Tertiary, beginning about 65 million years ago, was perhaps the most important period of time for forming economically valuable deposits of copper, silver, gold, lead, and zinc in Utah. A belt of volcanic activity swept south and west through Utah in response to heating and melting far below the surface due to converging plates.

The high-elevation plain of western Utah and eastern Nevada that had formed during earlier mountain building collapsed under its own weight, and the whole region began to extend to the west, widening into what is now the Great Basin. The extension took place in response to horizontal extensional forces that resulted in normal faults. These normal faults formed the typical north-south-trending mountain ranges and intervening basins that we see today from the Wasatch Mountains west to the Sierra Nevada, for example, the Snake Range in Nevada.

*Tertiary (66.4 to 1.6 million years ago)*

The last compressional mountain-building event to affect Utah, called the Laramide, followed close on the heels of the Sevier Mountain belt and lasted from about 70 to 50 million years ago. The Laramide mountain-building event is responsible for producing the Uinta Arch and changing the drainage system. In Cretaceous time, an integrated drainage system eroded the fold mountain belt, and sediments from it were deposited in the Cretaceous interior seaway. This Laramide thick-skinned, mountain-building event involving the Precambrian basement moved east and elevated the Cretaceous seaway.

The combined effect of igneous activity, accumulation of thick sequences of sedimentary rock, and compression, folding, and thrust faulting thickened the crust of western North America enormously. The thickened crust had a deep, hot, and weak root. When the compressive forces were relieved as North America overrode the Mendocino triple junction, the area began to extend in response to body forces from the thickened crust, convection in the underlying asthenosphere, and movement on the San Andreas Fault. As extension proceeded, the former area of thickened crust was segmented into a series of north-south-trending mountain ranges and intervening basins bounded by normal faults. The Oquirrh Mountains display their geology as a consequence of displacement on these range-bounding normal faults.



Courtesy University of Utah Press.

Figure 11. Igneous activity and volcanoes swept southward and westward through Utah from about 50 million years ago to 20 million years ago. Three dominant trends are recognized: The Park City-Bingham trend, the Tintic-Deep Creek trend, and the Wah Wah-Tushar trend.

Heat from within the Earth warmed the mantle, causing an elevation of the Cretaceous seaway. As a result, the integrated drainage system that had been eroding the Sevier Mountains was completely disrupted, and there was nowhere for the water to go. The rivers flowed into lakes.

After the Tertiary lakes disappeared, a period of intensive igneous activity swept through Utah. The rate of convergence of North America with the Pacific plate decreased again, and the inclination angle of the descending lithospheric slab increased. Extrusive and intrusive igneous rocks formed extensively for about 25 million years. A volcanic arc swept south and west across Utah as the convergent edge of western North America changed to a transform fault margin.

The major trends of igneous activity shown in figure 11 are the trend from Park City through the Wasatch to Bingham, a trend from Eureka (East Tintic Mountains)

## Volcanoes

Volcanoes form from igneous rock, rock that has been melted. Melted rocks are less dense than solid, cooler rocks so the melted rock is buoyant and rises from the source in the mantle through the crust and erupts on the surface. Crustal rocks through which the melted rock rises are saturated with water. The water near the melted rocks is heated, rises, and is replaced by cooler water, thus forming a convection cell. The heated water can then extract metals and sulfur from the igneous rocks and nearby crustal rocks.

west to the Deep Creek Mountains, and a third trend from the Tushar Mountains west to the Wah Wah Mountains. Each trend is associated with significant economic deposits of precious and base metals. The igneous rocks of the Wasatch belt are aligned along the east-west Uinta-Little Cottonwood lineament, a relic of the ancient suture of the Arizona and Wyoming cratons. Several base and precious metal deposits are associated with the Wasatch igneous belt, including those in the Park City, Little Cottonwood, and Big Cottonwood Mining Districts. These deposits include silver, lead, zinc, copper, molybdenum, and gold. These are the ages of the igneous rocks from east to west: Ontario, 30 million years old; Clayton Peak, 35.5 million years old; Alta, 33.4 million years old; and Little Cottonwood, 30.5 million years old. Bingham lies farther west and is 38.55 million years old.

### Quaternary (1.6 to 0 million years ago)

Quaternary events include the volcanic activity spectacularly displayed in Yellowstone Park and continued faulting and climate changes that advanced the glaciers and associated lakes in the Great Basin. Lakes accumulated because of the formation of north-south-trending mountain ranges and intervening valleys with no outlet for water. Lake Bonneville has a complex history that began about 30,000 years ago when the lake started to rise (figure 12). The lake rise was interrupted about 23,000 years ago at the Stansbury level at an elevation of 4,500 feet above sea level. Three additional interruptions in the rise of the lake have been recognized. The lake reached the Bonneville level, its highest point of 5,100 feet, about 15,000 years ago, when it overflowed at Red Rock Pass north of Preston, Idaho, and flowed down Marsh Creek into the Portneuf River, the Snake River, and the Columbia River. At its maximum elevation, Lake Bonneville was comparable in depth and area to Lake Michigan or Lake Huron.

The Bonneville flood at Red Rock Pass was catastrophic and involved nearly five trillion cubic meters of water with a peak flow of one million cubic meters per second. The flood lasted about 300 days. Erosion of the threshold to 4,740 feet produced the Provo level 14,000 to 13,000 years ago. Threshold control ceased, and the lake continued to fall due to evaporation to near its present level from 13,000 years ago to the present. As a consequence of unloading, the lithosphere has risen by as much as 70 meters in the central Bonneville basin with lesser amounts of uplift toward the edges of the ancient lake.

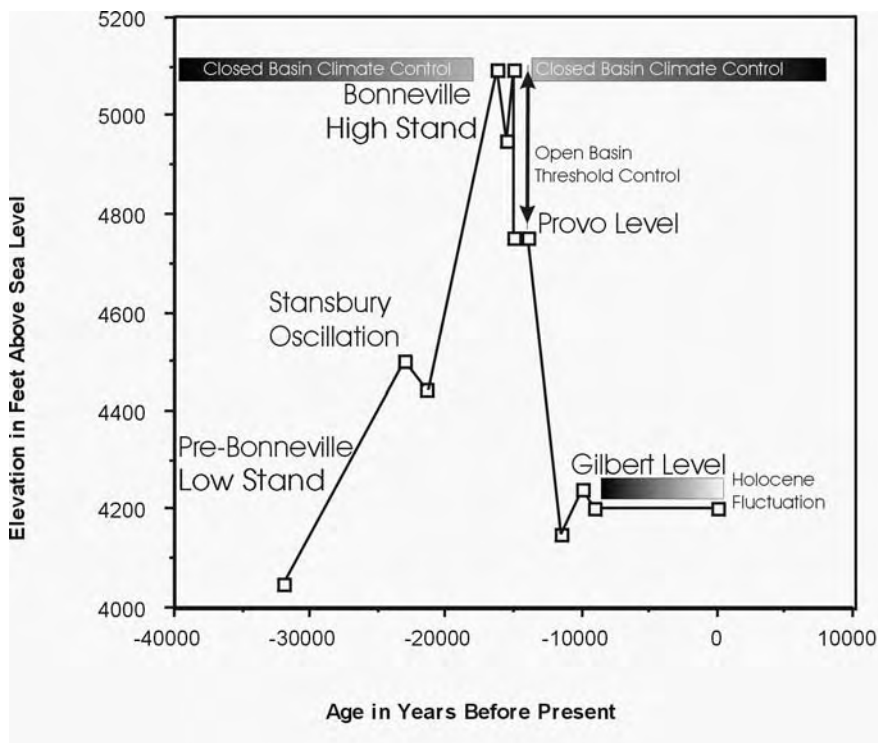


Figure 12. Hydrograph of Lake Bonneville showing lake levels in feet above sea level and age in years before the present.

The animals that lived on the shoreline included the extinct bear, horse, peccary, camel, bison, deer, musk ox, mastodon, mammoth, wolf, fox, and mountain sheep. The remains of these large mammals seem to indicate open parklands or grasslands situated in coniferous forests, very different from the present shoreline vegetation of cheatgrass, sagebrush, and scrub oak.

The present Great Salt Lake is a salty remnant of Lake Bonneville. The water inflow to the present lake comes from the Bear River (39 percent), precipitation (31 percent), the Weber River (13 percent), the Jordan River from Utah Lake and Provo River drainage (9 percent), and springs (3 percent). These inflows also carry dissolved salts that accumulate in the lake during evaporation.

The dissolved salts include sodium, calcium, potassium, magnesium, chloride, sulfate, and bicarbonate. Springs contain the highest concentrations and precipitation the lowest. The 30,000-year history of the lake has seen the addition of  $0.69 \times 10^{11}$  tons of chloride from rivers,  $0.15 \times 10^{11}$  tons of chloride from precipitation, and  $6.16 \times 10^{11}$  tons of chloride from springs. Some of the chloride now resides in the lake brine, some in water in the pore spaces in lake sediment, and some as salt beds that formed when the lake was so saline that the salt precipitated.

The climate changes that produced the lakes were linked to climate changes that caused ice to accumulate in the high peaks so that glaciers formed, similar to

## Building Mountains

The mountainous areas of Utah bear the record of repeated episodes of mountain building. The oldest rocks in Utah—exposed in the Wasatch above Farmington and in the Raft River Mountains—have the longest record of repeated mountain building.

All of the mountains, except the ones that decorate our present topography, resulted from collisions of lithospheric plates. The mountains we see now, though they expose folding and faulting from earlier collisions, resulted from extension and collapse of thickened mountainous crust.

Mountains formed at eight intervals in the development of the western United States. While all of the events did not take place in Utah, they influenced the type of sedimentary rocks that accumulated here. Each of the mountain-building events possesses the following characteristics to some degree: folding, thrust faulting, intrusive igneous rocks, volcanic rocks, and a wedge of clastic sediments from erosion of the mountains.

the glaciers that are present in the Chugach Mountains in Alaska today. The climate changes that produced the lake and then allowed it to dry up are indicated by the relationship of the lake levels to glaciation. During the lake rise, a large continental glacier covered the northeastern part of Canada and the northern part of the United States. This ice sheet had a profound effect on the climate of Lake Bonneville. Valley glaciers also occupied the canyons of the Wasatch Mountains and formed the present topography of Mount Timpanogos with its horns and cirques. Of these glaciers, two reached the level of Lake Bonneville: the Little Cottonwood and Bells Canyon glaciers. The maximum glacier advance occurred about 22,000 years ago, long before the maximum rise of the lake.

Computer modeling of climate suggests that if the mean annual temperature decreased by seven degrees centigrade, evaporation would decrease and permit the lake to rise. Similar modeling studies of glacier dynamics suggest that the glacial climate was as much as 15 degrees cooler than today and that the glacier could be maintained at the mouth of Little Cottonwood Canyon if precipitation were 75 percent of the present amount. Maximum glacier advance occurred during a time when the climate was cooler and drier. The lake rose to the Bonneville level during a receding glacier period when the climate may have been warmer and wetter. The lake then fell below the Provo level as the climate changes permitted evaporation to exceed precipitation and inflow. When the lake was at its maximum capacity, the lake effect added substantially to precipitation and helped maintain the level.

## ECONOMIC DEPOSITS

A metallic mineral deposit is a concentration of chemical compounds containing gold, silver, copper, lead, and zinc. To be economical, a deposit requires concentration by many orders of magnitude over average abundance. The average abundance

## Mountain-Building Events

Precambrian mountain-building events affecting Utah include these:

First, mountain building produced the metamorphic rocks of the Wyoming craton 2.5 to 3.5 billion years ago. Second, mountain building produced the metamorphic rocks of the Matzatzal craton in Arizona. Third, mountain building resulted from accretion of the Arizona craton to the Wyoming craton 1.6 to 1.8 billion years ago, called the Cheyenne event.

Paleozoic mountain building events affecting Utah include the following:

1. The Antler Mountains in Nevada are Devonian. The thrust faulting associated with this event is known as the Roberts Mountain thrust and is exposed in eastern Nevada. The volcanic and intrusive igneous rocks are part of the Sierra Nevada now. The sediments derived from this mountain range were deposited in the Devonian sea in western Utah and eastern Nevada, for example, the Stansbury formation on Stansbury Island. This mountain-building event was associated with the accretion of a volcanic island arc to the edge of the North American craton.

2. The Ancestral Rockies in eastern Utah, Colorado, and New Mexico are Pennsylvanian. The thrust faulting here was probably deep seated and involved much of the Precambrian crystalline basement. The sediments derived from these mountains filled the Pennsylvanian Paradox Basin in southeastern Utah.

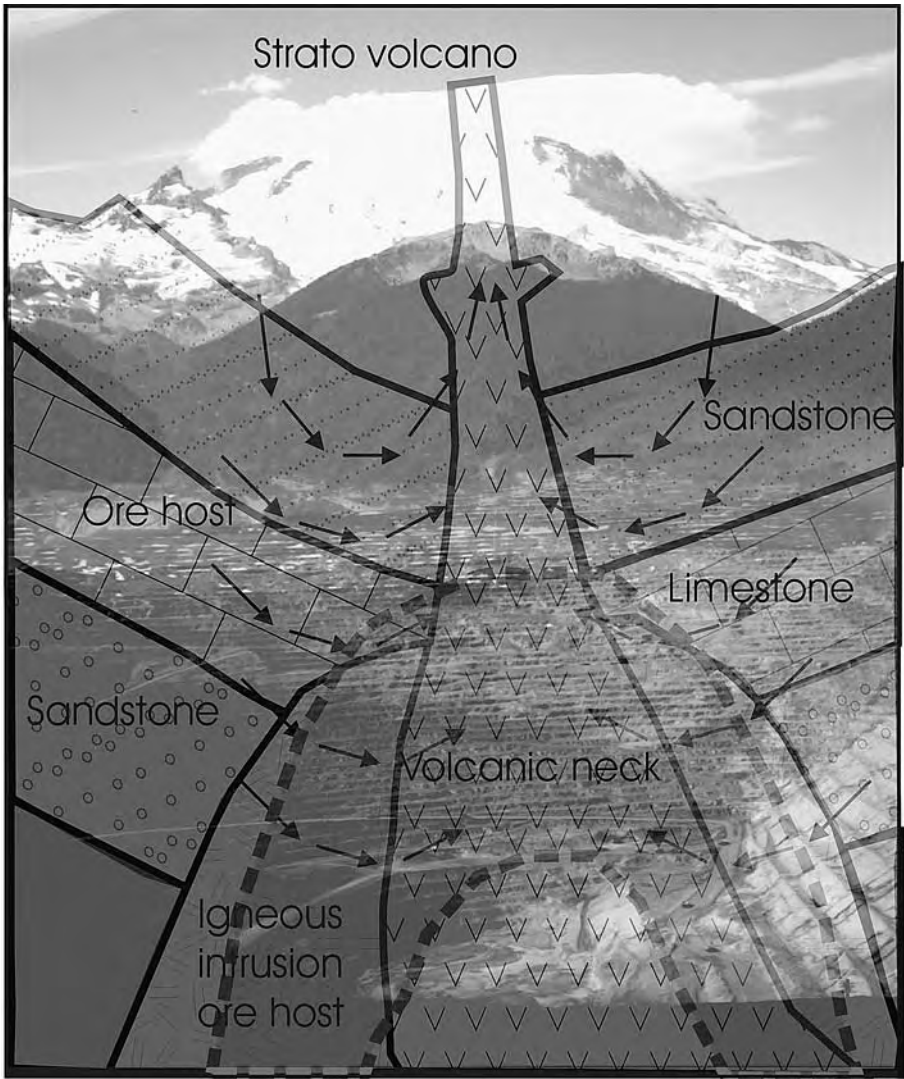
3. The Sonoma mountain-building event involved accretion of a second island-arc complex to the western edge of North America in Permian to Triassic time. The thrust-fault system associated with this event is the Golconda in central Nevada, and the igneous rocks are also part of the Sierra Nevada. Sediments from Sonomia probably helped fill the Oquirrh Basin of northwestern Utah.

Mesozoic and Cenozoic mountain building events include these:

1. The Nevadan mountain-building event created the Sierra Nevada in Jurassic time. Igneous rocks of Jurassic age core the Sierra Nevada and are distributed across western Utah in the House Range and Newfoundland Mountains, for example. The thrust fault associated with this event appears in Utah as the Manning Canyon Detachment. Debris eroded from the mountains appears in eastern Utah as the Jurassic Morrison formation.

2. The Sevier mountain-building event strongly affected Utah in Cretaceous time, producing the Willard-Paris and the Charleston-Nebo thrust faults. The igneous rocks are part of the Sierra Nevada. The debris eroded from this mountain range occurs in the Indianola conglomerate in central Utah and the Echo Canyon conglomerate in northern Utah.

3. The Laramide mountain-building event took place at the end of the Cretaceous and the beginning of the Tertiary (80 to 40 million years ago). The Laramide's most prominent mountain range is the Uinta Mountains. Less prominent features include the San Rafael Swell, the Water-pocket Fold, and the Monument uplift.



Courtesy University of Utah Press.

Figure 13. A schematic model shows the formation of deposits of valuable metals such as Bingham, Utah. Here, in a reconstruction of what Bingham was like, a large strato volcano similar to Mount Ranier was formed and in its roots circulating water indicated by the arrows extracted metals from the igneous rocks and possibly surrounding sediments and deposited them in an inverted, saucer shaped deposit within the intrusive igneous rocks at depth. Mining of the deposits at Bingham has produced the open-pit mine benches. The volcano no longer exists at Bingham; it was eroded away long ago.

of gold in granite is about two parts per billion parts of rock. The concentration required for an economical ore deposit is approximately two parts per million parts of rock, a thousand times more. So geological processes must concentrate the gold by a thousand times and must then transport the gold or copper or other valuable metal to someplace where it can be deposited in concentrated form, for example, Bingham, or Eureka, or Kimberly in the Tushar Mountains in southern Utah.

The transporting medium is a fluid. It can be water or magma. Water can come from magma or the ocean or from precipitation. Water is invariably involved in Utah ore deposits. The mechanism for depositing the ores in concentrated form can be cooling of the fluid, mixing fluids of diverse compositions, or chemical reactions as the water interacts with the rocks. These mechanisms change the ability of the water to maintain materials in solution.

Figure 13 shows a subsurface igneous intrusive that has reached the surface and formed a volcano, a big edifice such as the steep-sided composite volcano at Mount Rainier. The subsurface rocks include a sequence of sedimentary rocks deposited on the Precambrian basement. The pore spaces within the sedimentary rocks are filled with water, and the igneous rock heats up that water. Hot water is less dense than cold, and so it rises. Arrows indicate the hot water rising to the surface; it may produce hot springs similar to hot springs in Yellowstone Park. Lines of equal temperature are elevated toward the surface. At the surface, some boiling springs may occur. Cold meteoric water that falls on the ground circulates down because it is cold and dense. It gets heated; the density decreases so it rises to the surface. Water circulating through the rocks concentrates and precipitates valuable heavy metals. These kinds of deposits are associated with volcanic activity at lithospheric convergent margins.

Such processes have left Utah an important legacy of valuable deposits of copper, silver, gold, and other metals. Examples include the large copper deposit at Bingham and the productive silver, lead, and gold deposits in the East Tintic Mountains near Eureka. Ore deposits in the Tintic, Bingham, Park City, Big Cottonwood, Little Cottonwood, and American Fork Districts are variations on a three-part theme: carbonate sediments, faulting and folding, and igneous intrusion. The deposits differ only in detail.

### *Geology and Ore Deposits of the Wasatch Mountains*

The Wasatch Mountains near Salt Lake City display much of the geological history of Utah. The oldest rocks are Precambrian crystalline basement exposed east of Farmington (the Farmington Complex), and a small exposure occurs near the mouth of Little Cottonwood Canyon (the Little Willow Series). Younger Precambrian rocks of the Big Cottonwood Canyon series and still-younger Precambrian glacial deposits of Mineral Fork Tillite overlie these rocks. Shoreline and shallow-water continental-shelf deposits of Paleozoic time begin with Tintic Quartzite (Cambrian), Ophir Shale, and then a thick limestone, the Maxfield Limestone, indicating rising sea and migration of the shoreline eastward. Immediately east of Salt Lake City, Ordovician,

Silurian, and Devonian rocks are missing, and the Maxfield Limestone has been variably eroded away so that a thick sequence of Mississippian limestones directly overlies the Cambrian rocks. Pennsylvanian and Permian rocks in the Wasatch are much thinner than to the west in the Oquirrh Basin. Mesozoic rocks include marine limestones and the windblown sand deposit (Nugget) so prominent in southern Utah. Cretaceous rocks are clastics eroded from the thrust-fault sheets of the Sevier mountain-building event. All of these rocks are folded and thrust faulted. Later Laramide events are superimposed on the Sevier events. A chain of igneous intrusive rocks from Park City to Little Cottonwood Canyon postdates the Laramide. The Wasatch Mountains were later uplifted by the prominent Wasatch Fault.

One of the largest and most recent ore producers in this area was the Cardiff Mine. The greatest production came from the Deseret Limestone. Ore mineralization occurred where northeast fissures intersected the limestones in the footwall of the Alta thrust fault. The Cardiff Mine lies well up a glaciated fork of Big Cottonwood Canyon, which was itself glaciated above the confluence with Cardiff Fork. Hike up the fork on the old mining road littered with baseball-sized cobbles of limestone and quartzite. You reach the Price tunnel, where no ore was found but much water flows into the creek. Above here, at the Cardiff Mine site, spectacular cliffs of blue-gray limestone with bleached zones tower over the varied wood and metal debris from mining. Just above the mine, the Alta thrust fault can be seen placing older Cambrian Tintic Quartzite on top of younger Mississippian limestone and putting Precambrian tillite on top of the quartzite so the rocks appear in reverse order of age. The thrust fault played a leading role in forming the ores. The Alta stock was the heat engine that forced water to circulate through channels in the rock; the thrust fault and nearby northeast-trending fractures provided the fluid pathways, and the limestone neutralized the acid waters and precipitated the ores.

The famous Emma Mine in Little Cottonwood Canyon produced lead and silver from replacement of the Fitchville and Gardison limestones. Rich ore shoots occurred along northeast-trending fissures and within rocks that were especially permeable due to earlier fracturing along a thrust fault. Ore in the Emma and nearby Flagstaff Mine contained 60 ounces of silver per ton and 40 percent lead.

### *Park City*

The three of us—a mining engineer, a lawyer, and I—straddled the bench behind the gasoline-powered locomotive for the three-mile ride into the Ontario Number-Two Drain Tunnel. We headed straight into the core of the Park City anticline. We first passed through Keetley volcanic rocks, then through the Thaynes limestone that sometimes hosts ore, and then the Mayflower and Ontario igneous intrusives. The tunnel paralleled the Hawkeye-McHenry fault. At times tunnels bearing water entered from the south where lead-silver ore had been extracted along the fault. Tunnels used to explore side veins entered from the north. Where fluids and faults had destroyed the rock strength, heavy wood, steel, and concrete supported the

overlying layers of rock. Three miles into the mountain, we came upon the vertical shafts through which ore, men, and supplies were hoisted or lowered. The light at the tunnel mouth had long since shrunk to a pinpoint as we crouched down to avoid banging hard-hatted heads on the timbers, and cold water dripped down our necks. Our only illumination came from the battery-powered lamps attached to our helmets. As we quietly spoke, the water-saturated air caused our breath to condense in streams of steaming vapor.

The ore deposits of Park City occur in limestones and on faults that fed the metal-rich fluid into them. Little value is present in the igneous rocks whose heat circulated the water and whose heritage produced much of the ore. One particular limestone has been exceptional for its production of lead and zinc: the Jenny bed within the Park City formation. This limestone is about 20 feet thick and is a principal ore host in the Silver King, Ontario, Daly-West, and Judge Mines. The Weber quartzite is chemically less reactive than limestone, but it is brittle and fractures easily, and the fractures provide good conduits for ore-forming solutions that deposit ore along the way.

### *Bingham and the Geology of the Oquirrh Mountains*

The geologic history of the Oquirrh Mountains resulted in the formation of the Bingham copper deposit, the gold ores at Mercur, and the base and precious-metal deposits of Ophir and Stockton. Most of the mountain range is composed of sedimentary rocks: shales, limestones, and sandstones. These sediments were deposited in an ocean, but their position varied from near-shore sandstones to shales and limestones deposited far out to sea. A thick sequence of limestones and sandstones was deposited in an inland sea perhaps similar to the Black Sea today. Collision of South America with North America sent repercussions through western North America that included formation of the Ancestral Rocky Mountains and the creation of two important inland seas: the Paradox Basin and the Oquirrh Basin. The Oquirrh Basin in northwestern Utah was a deeply subsiding basin bounded by faults where a great amount of sediment accumulated, more than 20,000 feet. Thinner, younger deposits that also appear in the nearby Wasatch Mountains capped the thick basin fill.

The sequence of sedimentary rocks was folded and thrust faulted as a consequence of the convergence of North America and the Pacific plate during the breakup of Pangea. A series of anticlines and synclines is a prominent feature of the Oquirrh Mountains, and the accompanying Midas and North Oquirrh thrust faults are displayed in the northern part of the range.

Very early on Saturday morning, I mounted my horse Shorty for the ride from the end of the road in Ophir Canyon. I had driven up Ophir Canyon past the Ophir Hill Mine through the Ophir anticline. We were on the east limb of the Ophir anticline, and we rode across easterly inclined rocks, turned up Picnic Canyon, and continued riding to the crest of the mountain range. Lowe and Lewiston peaks were shrouded in thunderclouds, gale-force wind swept west across the ridges, and West

Canyon was obscured by more clouds far below us. Shorty walked carefully down the steep switchbacks and dugway trail covered with a few inches of snow to bring me to our lunch stop in the brilliant autumn-colored aspen grove. We saw a few elk and dozens of deer.

The Oquirrh Mountains are the richest hills in Utah and possibly in the world. Their richness stems from ores at Bingham, Stockton, Ophir, and Mercur. This unusual concentration is due to the sedimentary-rock host for the ore, faults that conduct the water that deposited the ores, and volcanic activity that supplies ore constituents and the heat engine that circulates the water.

The presence and action of a descending lithospheric slab underneath Utah melted rock that buoyantly rose in the vicinity of Bingham, creating a large strato-volcano and the associated volcanic rocks that erupted from the volcano. Water circulating from the igneous rock, water present in the rocks at the time of volcanic action, and water that precipitated on the mountains extracted metals from the igneous rock and surrounding sedimentary rocks to form the ores at Bingham and elsewhere.

The copper, molybdenum, and gold deposits at Bingham are largely contained within and related to an igneous-intrusive rock formation known as the Bingham stock. The Bingham stock has in turn been intruded by younger igneous rock in its northwestern part. Both of these igneous intrusions are cut by still younger and smaller igneous intrusions. The copper, molybdenum, and gold mineralization is disseminated throughout the igneous intrusions. The fluids that deposited the ore also converted the igneous rocks to a variety of minerals unlike the originals. Before mining the Bingham deposit contained 3.1 billion tons of ore averaging 0.73 percent copper, 0.043 percent molybdenum disulfide, and 0.013 ounces of gold per ton.

Thin limestone beds within the Pennsylvanian Oquirrh formation contain rich lead and zinc ore. The entire 8- to 15-foot thickness of the Lark limestone was replaced by lead and zinc minerals along a bedding plane fault. In the U.S. Mine, one of the major lead-zinc mines in the Bingham district, most of the mineralization existed within northeast-striking fissures in quartzite and igneous-intrusive rocks. Where these fissures crossed limestones, the ore mineralization extended laterally for variable distances. A third type of ore mineralization is also present at Bingham. Limestones in contact with the igneous-intrusive rock have been replaced by large quantities of constituents from the igneous-hydrothermal system, including copper.

### *Ophir*

Most of the ore bodies in the Ophir area are lead and zinc replacements of limestones. The ore bodies in the Ophir Hill Mine near the entrance to the town of Ophir occur in the limestone portions of the Ophir formation along fissures and faults.

### *Stockton*

The ores at Stockton occur at the intersection of the Great Blue limestone with north-south-trending fissures. The ore shoots are inclined to the northwest and may

contain 40 percent lead, about 20 ounces of silver per ton, and a small amount of gold. An igneous intrusive is present with an age of 39.4 million years.

### *Mercur*

The Mercur District extends from Ophir Canyon south to Five Mile Pass. The district has produced more than 3.5 million ounces of gold. The gold deposits occur in limestones of upper Paleozoic age that have been deformed into a series of northeast-trending folds. The gold is concentrated in a mineralized sequence of the lower member of the Mississippian Great Blue limestone. Although 32- and 37-million-year-old igneous rocks are present in the district, minerals reveal surprisingly old ages for the mineralization, more than 100 million years.

### *Tintic and East Tintic*

The town of Eureka lies at the foot of Eureka Ridge. A hike along the ridge from west to east traverses the sedimentary rocks that host the ores of the main Tintic District. To the north lies the small mining community of Eureka and to the south the smaller Mammoth town site. Mining structures of wood and metal and rock debris decorate the north-south-trending ore runs. The two principal mining areas are the Tintic and the East Tintic Districts. These two, though they are adjacent, differ in some important ways.

We were lowered a couple of thousand feet down the Chief Consolidated shaft; then, as the hoist cable stretched and the man cage bobbed up and down, we got off and walked to the nearest mine area, where rich lead-silver ore of the main Tintic District was being mined. The native silver along with the lead minerals glistened in the light of our headlamps. The ventilation air was cold, and we were told that so much water must be pumped out by the electric pumps that in case of a power failure, indicated by the occasional lightbulb going out, we had limited time to escape before the mine workings were completely submerged. In this main Tintic District, the major portion of the ore occurs as several northeast-trending ore runs that descend to the north. The most favorable host is the Bluebell dolomite of Silurian age.

Volcanic rocks, some extensively altered by circulating hot water from below much like Yellowstone Park, mostly cover the East Tintic District. Many of the mines in this area are hot from circulating water. Discovering the rich lead-zinc-silver deposits in the favorable sedimentary rocks beneath the volcanic cover provided a formidable challenge. Exploration was guided by the characteristics of the alteration in volcanic rocks and the complex assemblage of thrust, tear, and normal faults that acted as fluid-flow pathways.

To examine some of these deposits, we recruited a hoist operator and a couple of guides and descended the Eureka Lilly shaft. The air became hot and moist as we went down, and upon leaving the man cage, one of our guides burned his hand on the ringing handle to the telephone. (These telephones had a handle that must be cranked to ring the phone at the surface, hence a ringing handle.) The air temperature was

at least 120 degrees Fahrenheit, the top reading of the thermometer that I carried. We walked through the old mine tunnels to the Tintic Standard Number-One shaft, where no ore was discovered. We then walked to the Number-Two shaft, which was in the middle of the Tintic Standard ore body. Here lead-silver ore has completely replaced the Middle Ophir limestone along a complex system of faults related to thrust faulting known as the *pothole structure*. Fluids set into convective circulation by intrusions of hot igneous rocks reacted with the first limestone bed in the Paleozoic sequence. Then the limestone reacted to cause precipitation of the ore minerals.

### *Pine Valley and Silver Reef*

Interstate 15 descends toward St. George south of Cedar City. The high cliffs on the east mark the Hurricane Fault, and the dark mountains to the west are the Pine Valley range. Soon the core of the Virgin anticline appears with Quail Creek Reservoir at its southern tip. Rocks are tilted in opposite directions away from the crest of the anticline. It is this anticline and the thrust faults that accompanied its formation that affected the sandstone host for the silver deposits at Silver Reef. The ore horizon has been repeated three times by faulting as one layer of sandstone pushed over another. These are the same sandstone beds that host uranium ore to the east, but here only small amounts of uranium are present. Silver is the main attraction.

At Silver Reef and Leeds, the Pine Valley Mountains dourly preside over the lavishly colored red rocks to the south and east. These mountains are cored by an igneous intrusive formed 20.9 million years ago whose role in forming the silver deposits remains uncertain. The sandstone host for the silver ores is the Triassic-age Chinle. The silver was carried in solution in groundwater that moved through the porous and permeable river-channel sands. Chemical interaction with plant debris and associated bacteria resulted in precipitation of silver compounds that at times replaced tree limbs and trunks.

### *The Interior Seaway and Coal Deposits*

As you drive on U.S. Highway 6 from Spanish Fork Canyon to Price and beyond, imagine the scenery when the coal deposits were formed. The coarse red conglomerate in the Red Narrows of the canyon near the ghost town of Thistle and the junction with U.S. Highway 89, though younger than the coal, mark vigorous mountain streams eroding the folded and faulted older rocks of the mountains to the west. Such streams flowed east across a broad floodplain toward the arm of the ocean known as the Cretaceous interior seaway. Dinosaurs traversed this floodplain of swamps and forests covered by plants such as the ancient giant sequoia. Flood stages in the rivers covered the downed trees and prevented their decomposition. The result was layers of coal enclosed by beds of sandstone.

Major deposits of coal in Utah occur in Cretaceous rocks. The two most important areas where coal is mined are the Book Cliffs, where coal is found in several zones in the Blackhawk formation, and the Wasatch Plateau, a continuation of the

Book Cliffs to the southwest. The principal coal bed lies in the Blackhawk formation in the Mesa Verde group of the Upper Cretaceous. The coal beds formed about the same time as the Echo Canyon conglomerate along Interstate 80 east of Coalville and the Indianola conglomerate of central Utah. Dinosaurs, magnolias, fig cypress, palms, water lilies, and sequoias are major contributors to coal deposits. A third major accumulation of Cretaceous-age coal occurs in the Kaiparowits Plateau of Garfield and Kane Counties. The favorable circumstances that led to coal formation from middle to late Cretaceous time were luxuriant plant growth, favorable climate, low-lying coastal areas on the shoreline of the Cretaceous interior seaway, and relative subsidence of the area that led to the changing position of the shoreline. Coal deposits form on extensive delta plains adjacent to large rivers and along alluvial coastal plains where numerous small rivers shift their courses.

The prominent Andean-type mountain range in western Utah was associated with a broad downwarp in eastern Utah and western Colorado. This depression formed an arm of the ocean running from about the Gulf of Mexico to the Gulf of Alaska. Much fine-grained sediment accumulated in this ocean, but the shorelines had a different history. Vigorous mountain streams flowing east from the mountains produced thick accumulations of gravel and then meandered across a broad floodplain to reach the ocean. Coal beds formed from the dense accumulation of tropical plants that proliferated on this coastal plain.

Vigorous mountain streams like those in the Wasatch deposited conglomerates at the foot of the mountains during spring floods. After leaving their load of gravel at the foot of the mountains, the streams wandered across the floodplain watering a tropical jungle and depositing sand until they reached the sea. Some spring floods covered the plants, and succeeding layers of sediment preserved them as coal.

### *Oil and Natural Gas*

Oil formation requires a source bed, a reservoir rock, a trap, and a seal. The source bed must contain from 0.3 to 0.5 weight percentage of organic carbon with a high hydrogen to carbon ratio (0.7 to 1.5) and a low oxygen to carbon ratio (less than 0.1). The source bed must have been heated to a temperature sufficient to form petroleum, usually in the range of 130 to 140 degrees Centigrade, but time is important, too. Longer times require lower temperatures. If the temperature is too high, then only gas is produced. The reservoir rock must be both porous and permeable; the trap, for instance an anticline, permits the petroleum to accumulate because it is less dense than water, and an overlying impermeable bed such as shale prevents farther upward migration of the petroleum.

The oldest-known oil- and gas-bearing rocks in Utah are Devonian, although potential oil- and gas-bearing rocks may occur in the Chuar group of Precambrian age. Three geological areas have been major producers of oil and gas. They are the Paradox Basin in southeastern Utah, the Uinta Basin in northeastern Utah, and the overthrust belt of Utah and Wyoming. Oil is found in the Paradox and Honaker Trail formations

of Pennsylvanian age in the Greater Aneth field in the Paradox Basin, from the Green River formation of Tertiary age in the Altamont and Bluebell fields in the Uinta Basin, and from the Nugget and Twin Creek formations of Jurassic age in the overthrust belt in Summit County. Potential source beds include Twin Creek and Thaynes limestones, Mancos and Arapien shales, the Mesa Verde group, the Phosphoria (Park City formation), and lake sediments of the Green River formation. Other suggested source rocks are the Oquirrh formation and Kirkman and Flagstaff limestones.

### *Uranium Deposits of Southeastern Utah*

Uranium deposits in southeastern Utah are so distinctive that they are named for the region: Colorado Plateau uranium deposits. The uranium minerals have concentrated in sandstone bodies that filled river channels in the west-flowing Chinle rivers or the east-flowing Morrison rivers. The uranium accumulated in an idealized crescent-shaped deposit. Chemical reactions between the surrounding rocks and flowing groundwater mobilized the trace amounts of uranium that they contained. The uranium-charged water then moved easily through the sands and gravels of the ancient rivers until chemical reactions with plant debris or hydrocarbon precipitated the uranium.

Mesozoic rocks are the host for uranium-ore deposits that were intensively mined following World War II. The most famous mine in Triassic rocks is probably the Mi-Vida in Lisbon Valley southeast of Moab. This deposit, discovered in 1952, produced \$40 million worth of uranium. The major host rocks for uranium include the Triassic Chinle formation and the Jurassic Morrison formation. Creating uranium deposits in these rocks requires extraction from some source rock, transportation in porous and permeable rocks, and final deposition. Uranium occurs in two oxidation states:  $U^{+4}$  (reduced) and  $U^{+6}$  (oxidized). Uranium is soluble in the oxidized form, where it occurs in solution as uranyl ion  $UO_2^{+2}$ , and insoluble in the reduced form, where it occurs as the mineral uraninite  $UO_2$ . Uranium is extracted from granitic source rocks that contain an average of four parts uranium per million parts of rock by oxidized rainwater. The uranium is then transported in groundwater through porous and permeable rocks. Stream-channel sands in the Chinle and Morrison formations are ideal transportation pathways. The uranium is then precipitated by chemical reduction when the groundwater encounters organic matter such as logs or dinosaur bones in the buried paleo stream channel. Other important reducing agents include natural gas or petroleum-type hydrocarbons.

The early morning sun rises near the LaSal Mountains to the east and picks out the tips of red sandstone cliffs at Courthouse Rock. Green and purple sage still in shadow provides an aromatic accompaniment to the growing illumination of Arches National Park. To the west the huge, red, Wingate cliffs are like the sides of an enormous ship sailing in the red sea of the underlying Chinle formation. Jeep roads mark the uranium-bearing beds in the Chinle. The Chinle was also a prolific uranium producer in the San Rafael Swell to the northwest.

## GEOLOGY AND UTAH'S MINERAL TREASURES

Matt and Bill camped on the bank of the Muddy River near the heart of the San Rafael Swell in the shadow of Tomsich Butte. Small uranium mines and prospects decorated the Chinle exposures beneath the Wingate and Navajo sandstone cliffs. Early the next morning, they put on wading shoes and, with day packs filled with spare clothing, food, and a first-aid kit, set out down the Muddy toward the steep-walled and narrow canyon known as the Chutes of Muddy Creek. The trail guide had said that water was seldom more than ankle deep through the chutes. They alternately waded the river and walked on the sand banks until the canyon became so narrow that they were in the water all of the time. The water gradually deepened until it was chest high, and small irregularities in the footing caused them to sink deeper. Without flotation gear, they decided to turn back before reaching the end of the chutes at the Delta Mine.

The Muddy River originates in the high Wasatch Plateau, where it has cut its canyon into Tertiary-aged lake sediments. It flows south toward the San Rafael Swell, that large, bean-shaped, anticlinal fold that formed during the last episode of plate-convergence-driven mountain building. The river system has exhumed the swell by removing the overlying cover of lake sediments and superimposing its meanders. Continued exhumation has cut through the Mesozoic and into Paleozoic sediments. Before the river emerges from the swell, it flows through a high-walled, narrow slot canyon called the Chutes, cut through Navajo and Wingate sandstone. The river exits from the chutes into a softer, more mellow terrain and there, 400 feet above, on the cliffs on the left side of the canyon, is the Delta or Hidden Splendor Mine. The Muddy then joins the Dirty Devil River and finally the Colorado.

In its journey, the Muddy cuts through the Chinle and Moenkopi formations and deep into the late Paleozoic rocks. As it flows from the canyon gash cut into the Paleozoic into the more subdued terrain of the Moenkopi, high Wingate and Navajo cliffs above shelter the Delta Mine in the underlying Chinle sandstone. The uranium, vanadium, and copper ores are contained in ancient river-channel sand fillings, elongated, as are the river channels themselves, in a northwestern direction. Groundwater here extracted uranium and other metals from volcanic ash, flowed in the subsurface along easy pathways in the channel sands, and deposited the uranium in the trunks and limbs of fossil trees and other plant debris.

### SUMMARY

The rich and diverse geological history of Utah has provided source rocks for mineral wealth, host rocks for placing minerals, pathways to conduct the fluids that place the minerals, and driving mechanisms that produce the mineral deposits. The early marine history created the limestone host rocks that contain the rich metal deposits at Bingham, Tintic, Park City, Big Cottonwood-Little Cottonwood-American Fork, Mercur, and other places around the state.

Later, streams flowing from high mountains deposited gravels and sands that are the hosts for uranium in southeastern Utah and silver at Silver Reef. Rivers running west from the Ancestral Rockies to the sea deposited the Chinle formation while rivers running east from the Nevadan Mountains into the Sundance interior sea laid down the younger Jurassic Morrison formation. River channels are filled with coarse, permeable sand. These sands provided pathways to move groundwater and form uranium deposits in Triassic Chinle and Jurassic Morrison formations.

The younger Sevier Mountains supplied the water for rivers flowing east into the Cretaceous interior sea. These rivers watered the lush vegetation that was buried in flood stages to form coal deposits.

Igneous activity accompanying mountain building created the metal deposits at Bingham, Park City, Eureka, and elsewhere. Finally, the area was fragmented and extended by great north-south-trending normal faults, and erosion of the mountain ranges of the Great Basin and the Wasatch exposed the ore deposits for study and exploitation.