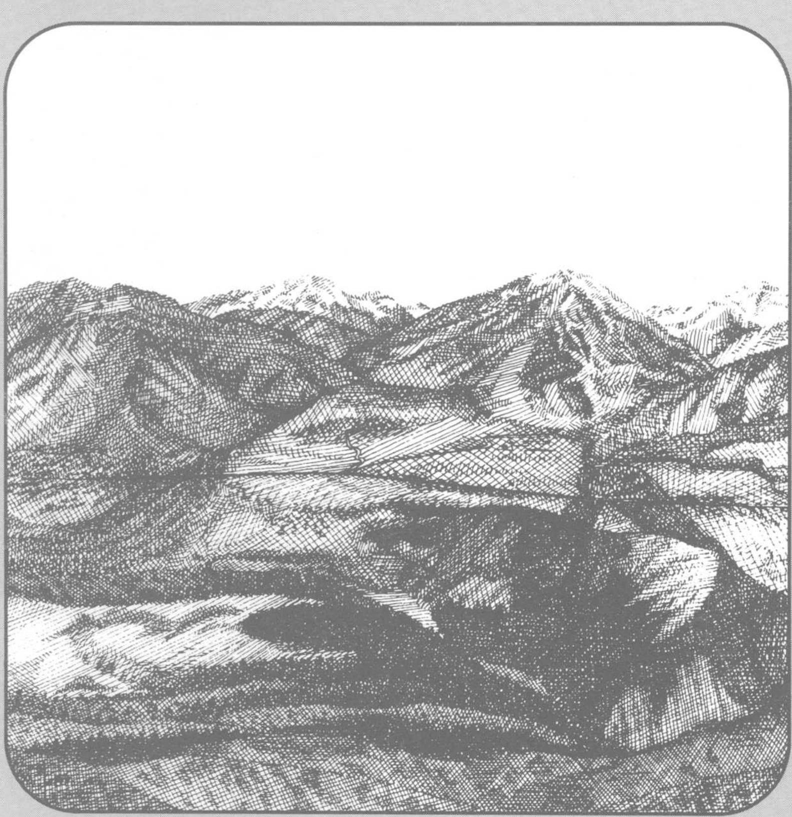
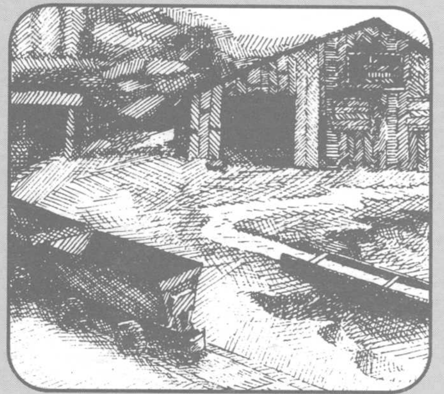
A The Geologic Story of the ASPEN Region





Mines

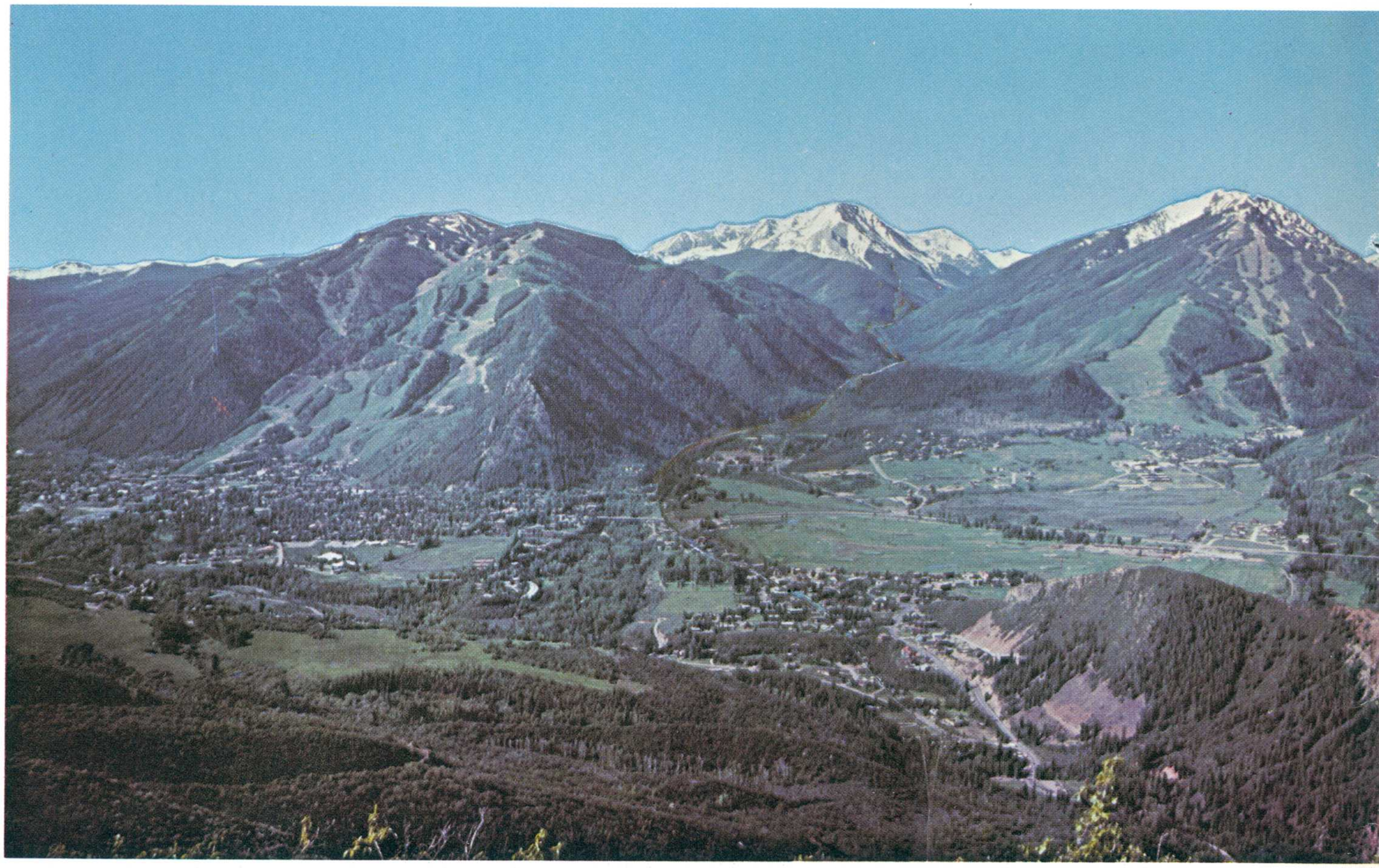
Glaciers

Rocks

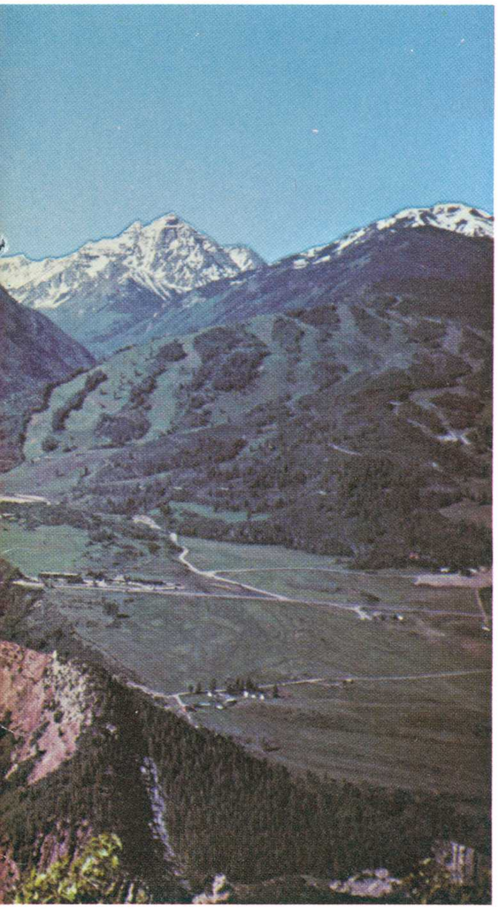
U.S. GEOLOGICAL SURVEY BULLETIN 1603

John Keith

The Geologic Story *of the* Aspen Region



Frontispiece.
The setting of Aspen. View south from slope of Red Mountain across the Roaring Fork Valley and up Maroon Creek (right) and Castle Creek (left). Mountains left to right are: Aspen Mountain, Hayden Peak, Highland Peak, Pyramid Peak, and Siever Mountain. Red Butte in foreground.



The Geologic Story of the Aspen Region —Mines, Glaciers and Rocks

By BRUCE BRYANT *and* PETER L. MARTIN

U.S GEOLOGICAL SURVEY BULLETIN 1603

DEPARTMENT OF THE INTERIOR
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Preface

This bulletin evolved slowly over a number of years, and we are indebted to many people for their help. J.C. Reed, Jr., read an early version by the senior author and encouraged him to continue the project. Formal reviews by S.W. Hobbs, V.L. Freeman, R.B. Raup, Jr., and M.T. Hait, Jr., led to further improvements. The junior author then rewrote much of the text to make it more readable for its intended audience. We thank E.T. Ruppel, P.L. Williams, C.L. Pillmore, A.C. Tarr, and R.B. Raup, Jr., for encouraging us to complete the report. A.C. Christiansen helped us improve the design and content of the illustrations. Final design and drafting of illustrations were by Arthur L. Isom.

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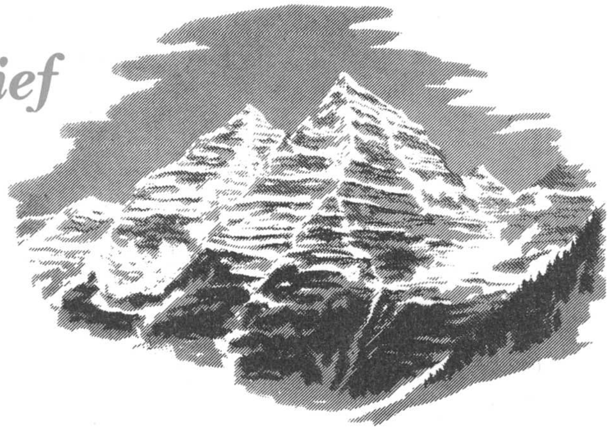

The town of Aspen nestles in the Roaring Fork valley of western Colorado (Frontispiece), surrounded by imposing peaks of the Elk Mountains and the Sawatch Range. More than a quarter of a million visitors now flock to this Rocky Mountain resort each year. In winter they are drawn by the deep powder snow that adorns hundreds of miles of ski trails; in summer they come for hiking, climbing, hang-gliding, and star-gazing (both kinds). The town also plays host to many academic and business conferences, and to the world-famous Aspen Music Festival. But little over a hundred years ago there was no town here; 10 million years ago there was no valley here; and 100 million years ago there were no mountains here.

The remarkable scenery of the Aspen region reflects a long history of struggle involving water, ice, gravity, wind, and powerful forces within the Earth. This history encompasses billions of years of building, breaking, heating, cooling, crushing, and folding of the Earth's crust.

Geologists estimate the age of the Earth as 4.6 billion years. A billion years is a thousand million years.[1] This is too long a time for a human to comprehend, for most of us live our lives in less than a century. But if we could somehow compress these billions of years into one calendar year, each day would span 12.6 million years, and two lifetimes would fit within a second. (See "The Geological Year" on fig. 14.)

Geologic time scale, p. 28

It is midnight on December 31 of our geological year, and 4.6 billion eventful years have elapsed since the Earth first took form last January 1. On this calendar, the oldest rocks now found in the Aspen region were first deposited in early August (perhaps 1.8 billion years ago) and were formed into their present aspect in mid-August (1.7 billion years ago). We can only guess what conditions were like in this area before that time. We know that the ground was scorching and the atmosphere was poisonous when the Earth first formed: mammoth volcanoes belched molten rock and gas; giant meteorites pockmarked the planet; and any rain that fell boiled away instantly, only to fall again.

Oldest rocks, p. 29

Yet, by the time the oldest rocks around Aspen were formed, the Earth had cooled enough to accommodate oceans, for some of the ancient rocks were deposited as marine sediments. Others had a volcanic origin. The very same processes that deposited these rocks soon conspired to bury them. Through millions of years new rock accumulated above the oldest Aspen rocks, eventually burying them 6 miles or more below the surface.

Sillimanite, p. 29

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[1] This is North American usage. People in many other areas define a billion as a million million. That amount would be a thousand of our "billions."

Schist, gneiss, and amphibolite, p. 29

Then, about 1.7 billion (or 1,700 million) years ago, forces deep in the Earth bent and folded the rocks into intricate patterns; great heat and pressure metamorphosed them to schist, gneiss, and amphibolite; and the accumulation of sediments overhead ceased (fig. 1*A*). Instead, the land surface began rising; it emerged from the sea, and rain and wind began stripping away the uppermost layers.

Quartz monzonite, p. 29

In early September of our geological year (about 1,450 million years ago), hot magma from deep within the Earth forced its way into the oldest Aspen rocks and cooled to form a younger granite (fig. 1*B*). Meanwhile, the slow ascent of the rocks continued; the warped layers of ancient metamorphic rock and the newly formed granite cracked, twisted and broke as they pushed toward the surface.

The uplifting and erosion were nearly completed by the end of Precambrian time about 570 million years ago—November 16 on our geological calendar. The time after this date comprises just 6 weeks of our geological year, but our knowledge of geological history is far more complete for this short period than it is for the preceding 4 billion years.

Early Paleozoic, p. 32

About 530 million years ago, a shallow sea crept across the Aspen area, and the Precambrian igneous and metamorphic rocks were buried by marine sediments. For more than 200 million years—about 16 days of geological time—this shallow sea advanced and retreated, alternately flooding and draining the low-lying land. None of this happened suddenly; a shoreline that moves a few inches a year can easily migrate hundreds of miles in a few million years. Each advance left a distinctive layer of sediment, which eventually compacted to rock (fig. 1*C*). Some of these layers eroded away soon after they were formed, but most remain today as thin rock units in the mountains surrounding Aspen, and many contain the fossil remains of fish, coral, mollusks, and other creatures that lived in that ancient sea.

Late Paleozoic-early Mesozoic, p. 33

About December 7 of our geological year (315 million years ago), land near to the Aspen area began to rise. By the 12th, there was a full-blown mountain range southwest of the area (fig. 1*D*) and another one northeast of it. These were not the Rocky Mountains; they have been called the "Ancestral Rockies." These predecessors of our present mountains extended generally from southeast to northwest across the area now called Colorado.

Eagle basin, p. 33

Hematite, p. 35

Maroon Formation, p. 35

The Aspen area at that time lay in a lowland, and the streams that gushed forth from the southwestern mountains deposited sediments thousands of feet thick in the area. The iron-bearing minerals these sediments carried were exposed alternately to moisture and to warm air, which transformed those minerals into ones resembling rust. Thus a rusty-red hue was imparted to the rocks formed from these sediments. Today, these red beds of rock are more than 2 miles thick in parts of the region; these are the rocks that make Red Mountain red and the Maroon Bells maroon (figs. 10 and 20).

Late Mesozoic, p. 37

Entrada Sandstone, p. 37

Morrison Formation, p. 38

By December 20 of the geological year (150 million years ago), the forces of erosion had leveled the Ancestral Rockies. The wind blew unimpeded across the flat land, bringing sandstorms that covered the old red beds with several feet of yellowish- or pinkish-gray sand (fig. 1*E*). A shallow sea occupied the heart of the continent at this time, and many wandering streams flowed toward it from the high ground that lay far to the south and west. As these streams meandered sluggishly across the low-lying Aspen area, they dropped their loads of silt, clay, sand, and lime. These sediments formed multicolored layers of rock that today look like rainbow stripes in a few of the gullies near Aspen.

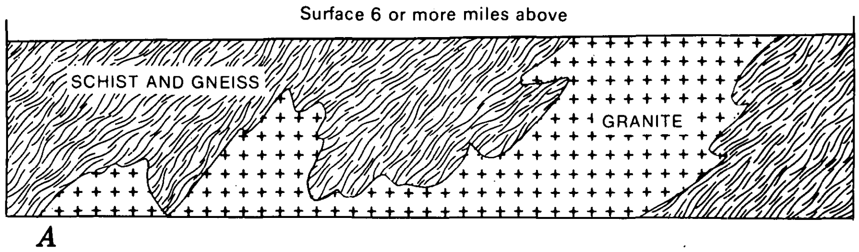


Figure 1*A*. Diagrammatic section deep in the crust through the Aspen region about 1,700 million years ago (early Proterozoic time) showing the granite that invaded the folded and layered rock at the level now exposed at the surface.

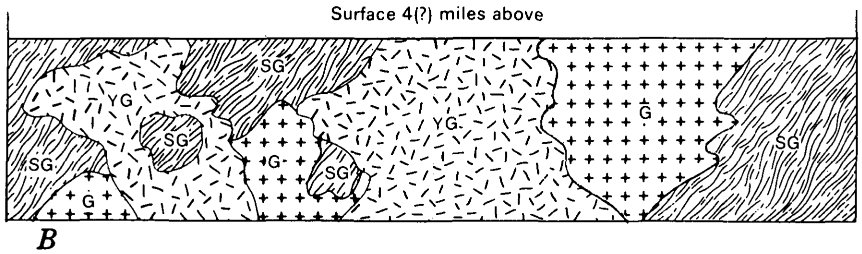


Figure 1*B*. Diagrammatic section through the Aspen region about 1,450 million years ago (Middle Proterozoic time). SG, schist and gneiss; G, granite; YG younger granite.

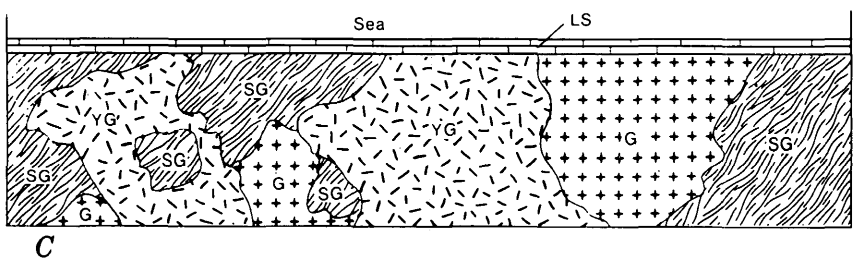


Figure 1*C*. Diagrammatic section through the Aspen region about 400 million years ago (Devonian time). SG, schist and gneiss; G, granite; YG, younger granite; LS, limestone.

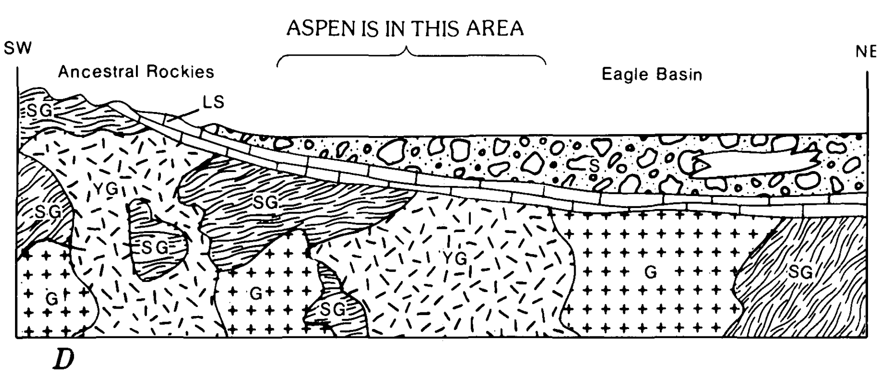


Figure 1*D*. Diagrammatic section through the Aspen region about 280 million years ago (Permian time). SG, schist and gneiss; G, granite; YG, younger granite; LS, limestone; S, sedimentary rock.

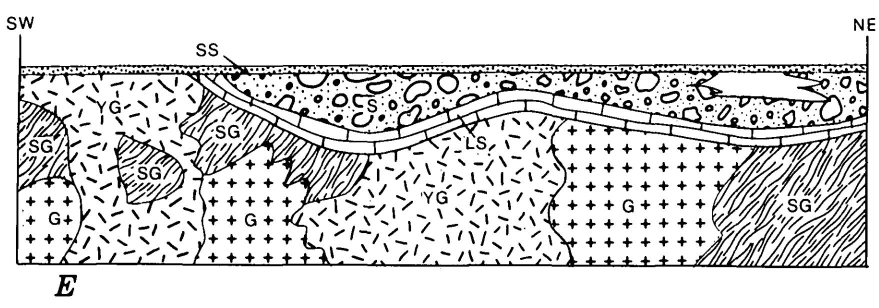


Figure 1*E*. Diagrammatic section through the Aspen region about 145 million years ago (Jurassic time). SG, schist and gneiss; G, granite; YG, younger granite; LS, limestone; S, sedimentary rock; SS, sandstone.

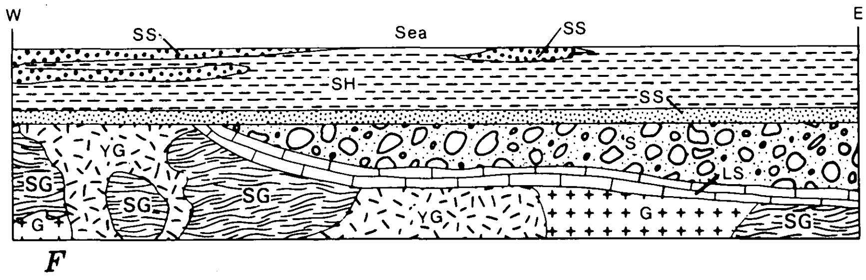


Figure 1*F*. Diagrammatic section through the Aspen region about 75 million years ago (Late Cretaceous time). SG, schist and gneiss; G, granite; YG, younger granite; LS, limestone; S, sedimentary rock; SS, sandstone; SH, shale.

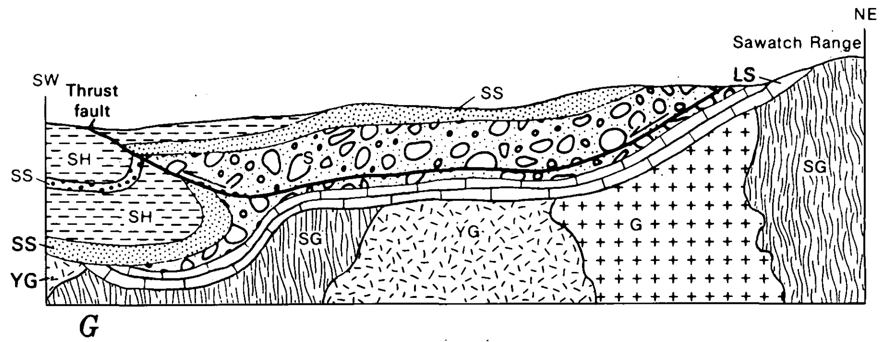


Figure 1*G*. Diagrammatic section through the Aspen region about 70 million years ago (Late Cretaceous time). SG, schist and gneiss; G, granite; YG, younger granite; LS, limestone; S, sedimentary rock; SS, sandstone; SH, shale.

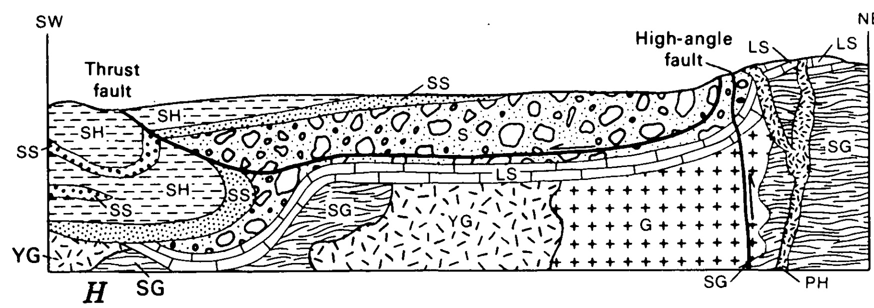


Figure 1*H*. Diagrammatic section through the Aspen region about 65 million years ago (about the end of Cretaceous time). SG, schist and gneiss; G, granite; YG, younger granite; LS, limestone; S, sedimentary rock; SS, sandstone; SH, shale; PH, porphyry.

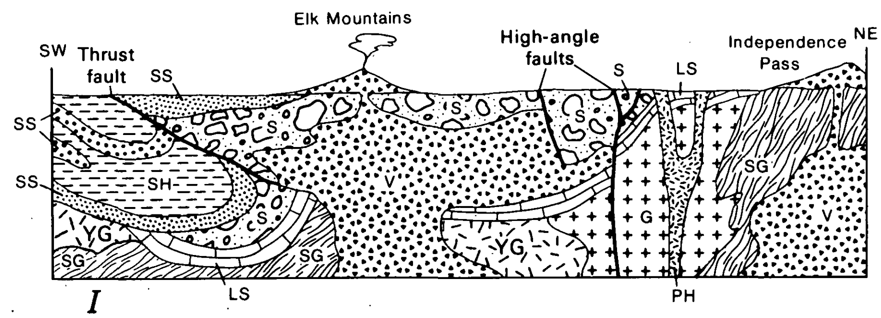


Figure 1*I*. Diagrammatic section through the Aspen region about 34 million years ago (Oligocene time). SG, schist and gneiss; G, granite; YG, younger granite; LS, limestone; S, sedimentary rock; SS, sandstone; SH, shale; PH, prophyry; V, volcanic and intrusive rock.

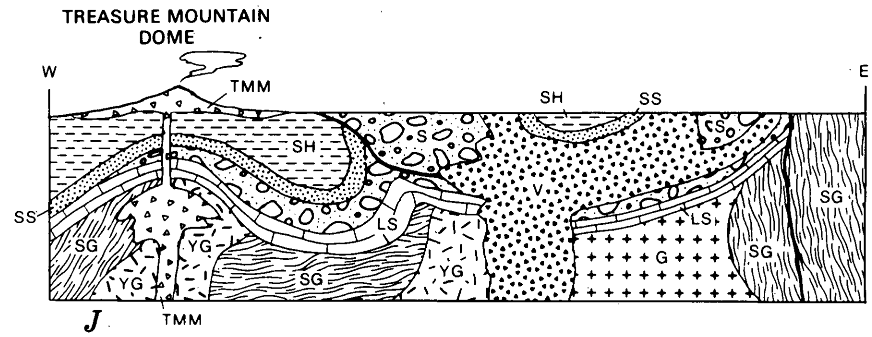


Figure 1*J*. Diagrammatic section through the Aspen region about 12 million years ago (Miocene time). SG, schist and gneiss; G, granite; YG, younger granite; LS, limestone; S, sedimentary rock; SS, sandstone; SH shale; V, volcanic and intrusive rock; TMM, Treasure Mountain Magma.

As the land around Aspen sank lower, the sea encroached from the north and east, covering the stream deposits with beach deposits, which in turn were covered by offshore deposits. About 180 million years after the rise of the Ancestral Rockies had driven the sea away, the Aspen region was again under water (fig. 1*F*). This time the sea remained for 45 million years—from December 22 to December 26 on our geological calendar. Dinosaurs walked on nearby beaches during this time, and the sea was populated by ammonites—extinct cousins of the pearly nautilus—which left their coiled, chambered shells as fossils in the dark-gray shale that collected a mile deep.

Dakota Sandstone, p. 38

Ammonites, p. 39

Mancos Shale, p. 38

Seventy-two million years is less than 6 days of our geological year. As recently as that, the rocks at the top of Mount Elbert—Colorado's highest peak—lay more than 2 miles beneath the floor of an ancient sea. Then, between 70 and 65 million years ago, there occurred an event so scientifically startling that geologists have chosen to call it a "revolution." Driven by forces deep within the Earth, the sea floor began to rise about 5 inches per century, and it continued to rise for five million years. The result: a new mountain range extended from Alaska to Mexico; finally, the modern Rocky Mountains had taken form.

Laramide orogeny, p. 40

Near Aspen, the Sawatch Range rose at this time, and a 4-mile-thick sheet of stratified rock broke loose and slid down its side, creating a geological jumble. Molten rock intruded the upper part of the rising crust, and sent superheated ground water circulating through nearby rocks. The superhot water dissolved, redistributed, and concentrated particles of silver, lead, and zinc to form rich deposits of valuable ore.

Elk Mountains thrust sheet, p. 40

Aplite, p. 40

It could hardly be said that the Rockies "sprang up overnight," for they rose just a few inches each 100 years. But in geological terms this was an uncommonly rapid rise. The many layers of sedimentary rock that had accumulated for half a billion years now rose and were consecutively eroded away in just five million years (fig. 1*G*, *H*). Bent and broken fragments of those sediments now sit at odd angles around the sides of the towering mountains, revealing the history of that half billion years. Dark-gray shale from the ocean bottom lies over sandstone from ancient beaches; the beach deposits sit on rocks of many colors laid down by sinuous lowland streams; and beneath these, wind-deposited sandstone covers the roots of the Ancestral Rockies and the thick red sediments they had shed. Rocks older than these bear the scars of two episodes of uplift and erosion; their thin layers remind us of a shallow sea that washed across the Aspen area 500 million years ago. When the Rocky Mountains rose, it was as if the work of 40 days had been undone in 10 hours. On our geological calendar, those climactic 10 hours occurred December 26.

Following the rise of the modern Rockies, the Aspen area was rather quiet for 30 million years or so. Then, between 35 and 32 million years ago, a large body of molten rock moved into place deep beneath the area and thrust up the high peaks of the Rocky Mountains still farther (fig. 1*I*). In many places this magma broke through to the surface, and volcanoes covered the terrain with vast flows of lava and ash. Intense heat changed some parts of the old red beds to gray or greenish gray, and superheated ground water swept through the old sedimentary layers, leaving concentrations of minerals in diverse places. On our geological calendar, this was the morning of December 29.

Oligocene Epoch, p. 43

Granodiorite, p. 43

Hornfels, p. 43

The remainder of the geologic year has mostly been a time of erosion in the Aspen area, although sporadic volcanic eruptions continued nearby (fig. 1*J*) until about 1½ million years ago (9 p.m., December 31). No sooner had the lava flows cooled than they began to be washed away; today, their remnants are found only on the tops of a few hills in the Aspen area.

Late Tertiary time, p. 45

Regional uplift, p. 13 and 49

Sometime in the last 20 million years, the whole western part of the United States began rising slowly, and it may still be rising. Streams running off the Rockies cut deep gorges in the new high ground; the higher it rose, the deeper they cut. The spectacular canyons of Utah and Arizona were carved in this fashion.

Pleistocene Epoch, p. 15

Yet, water has not been the only agent of erosion at work on the last day of our year. Two million years ago (about 8:30 p.m. on our geological "New Year's Eve"), the world turned dramatically colder. Deep snowfields covered the Rockies, and glaciers thousands of feet thick crept down mountain valleys, carving and molding the landscape.

Downcutting, p. 19–20 and 47–49

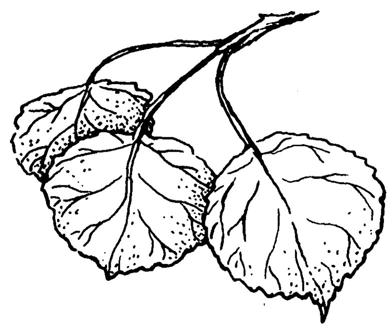
The glaciers advanced and retreated many times in the last 3 hours of our geological year; they sometimes completely disappeared for thousands of years. One of the earliest glaciers left deposits on the top of Red Mountain, which now rises 2,000 feet above the town of Aspen. Evidently, these deposits mark the level of the valley floor less than 2 million years ago. Since that time, water, ice, and landslides have cut the valley down to its present level.

Outwash terraces, p. 19

As little as 20,000 years ago, 2¼ minutes before the end of our geological year, glacial ice still reached down the valleys of Maroon and Castle Creeks as far as the present city limits of Aspen. By 15,000 years ago the ice had retreated upstream. Its glacial meltwater laid down a flat terrace of gravel, which provided a convenient foundation for Aspen and its airport.

History, p. 7–12

Sometime during this most recent glacial retreat, primitive men first appeared in the Roaring Fork valley. They had emigrated from Asia by way of Alaska. It was not until the last half-second of our geological year that the men arrived who dug mines, built houses, and eventually established ski slopes.



The History of the Aspen Region--
From Mining to Recreation

Over a hundred years ago F. V. Hayden and W. H. Holmes studied the rocks and scenery of the Aspen region (fig. 2) and much of Colorado during the U.S. Geological and Geographical Survey of the Territories, better known as the Hayden Survey. Henry Gannett, for whom the highest peak in Wyoming is named, measured the altitudes of mountains and drew topographic maps, and W. H. Jackson photographed the rugged terrain. These explorers found no settlements or roads near Aspen, but their travel was aided by Indian foot trails, as the region was the summer hunting grounds of the Ute tribe. On the south side of the Elk Mountains they found a few struggling mining camps.

These pioneering scientists laid the groundwork for the study of the geology of the Aspen region on which we build today. They also were pioneers in the esthetic appreciation of the spectacular scenery of the region, for Hayden wrote the following tribute to that scenery in his report for 1874 (published 1876).

> The gorges or canons cut by Castle and Maroon Creeks and their branches are probably without a parallel for ruggedness, depth, and picturesque beauty in any portion of the west. The great variety of colors of the rocks, the remarkable and unique forms of the peaks, and the extreme ruggedness, all conspire to impress the beholder with wonder.

The geologic maps based on the work of the Hayden Survey in Colorado were published in 1877 at the beginning of the great silver mining boom at Leadville. Prospectors saw on those maps that the rocks that contained the silver at Leadville formed a belt farther west, and in the summer of 1879 a small band of men from Leadville located the first mining claims where that belt of rocks crosses the Roaring Fork valley. That discovery was on the side of the ridge west of Spar Gulch overlooking the present city of Aspen (fig. 3). During the next few years prospectors followed the belt of rocks mapped by the Hayden Survey along the edge of the Sawatch Range north and south of Aspen. At the same time, prospectors scoured other areas in the Elk Mountains southeast of Aspen.

Ashcroft, on Castle Creek south of Aspen, sprang up in expectation of a boom before Aspen was well established, and a small village called Highland flourished briefly at the junction of Castle and Conundrum Creeks (fig. 24). Early mining at Ashcroft did not reveal large ore deposits, so in 1884, after the richness and extent of the ores at Aspen were established, the residents picked up and moved much of Ashcroft to Aspen.

But Aspen was very difficult to reach in the early mining days. The nearest railroad was on the Arkansas River 40 miles to the east, on the other side of the rugged Sawatch Range (fig. 2). Consequently, food, clothing, machinery, and blasting powder had to be shipped across the mountains on burros (or "jacks") or by wagon, and all ore had to be taken out the same way. One shipping route traversed Independence Pass from Granite, and another crossed Cottonwood Pass from Buena Vista to Taylor Park and then reached Aspen by way of Taylor Pass (fig. 4).

Because of these transportation difficulties, some ore was smelted at Aspen during the years before railroads were built. The miners used charcoal to fire their smelters, and one can still see the remains of ovens where wood was burned to produce charcoal on the west side of the Castle Creek valley opposite Queens Gulch.

Adding to these problems were boundary disputes, which also slowed production from the Aspen mines in the middle 1880's. According to the so-called Apex Law, the owner of a vein of ore exposed on the surface within his claim could follow that vein to depth, no matter what direction the vein followed nor what distance it continued (fig. 5). Predictably, those who did not have ore at the surface argued that ore did not occur in continuous veins, but rather in unconnected masses, pockets, and impregnations here and there in the limestone and dolomite, and therefore that it could be mined only to the vertical projection of the boundary of the claim. The owners of the claims took the argument to court, and spent a million dollars developing their cases. The adversaries hired geologists and, more importantly, lawyers to determine whether or not the ore at Aspen occurred in continuous veins. Although the Apex claimants finally won this legal

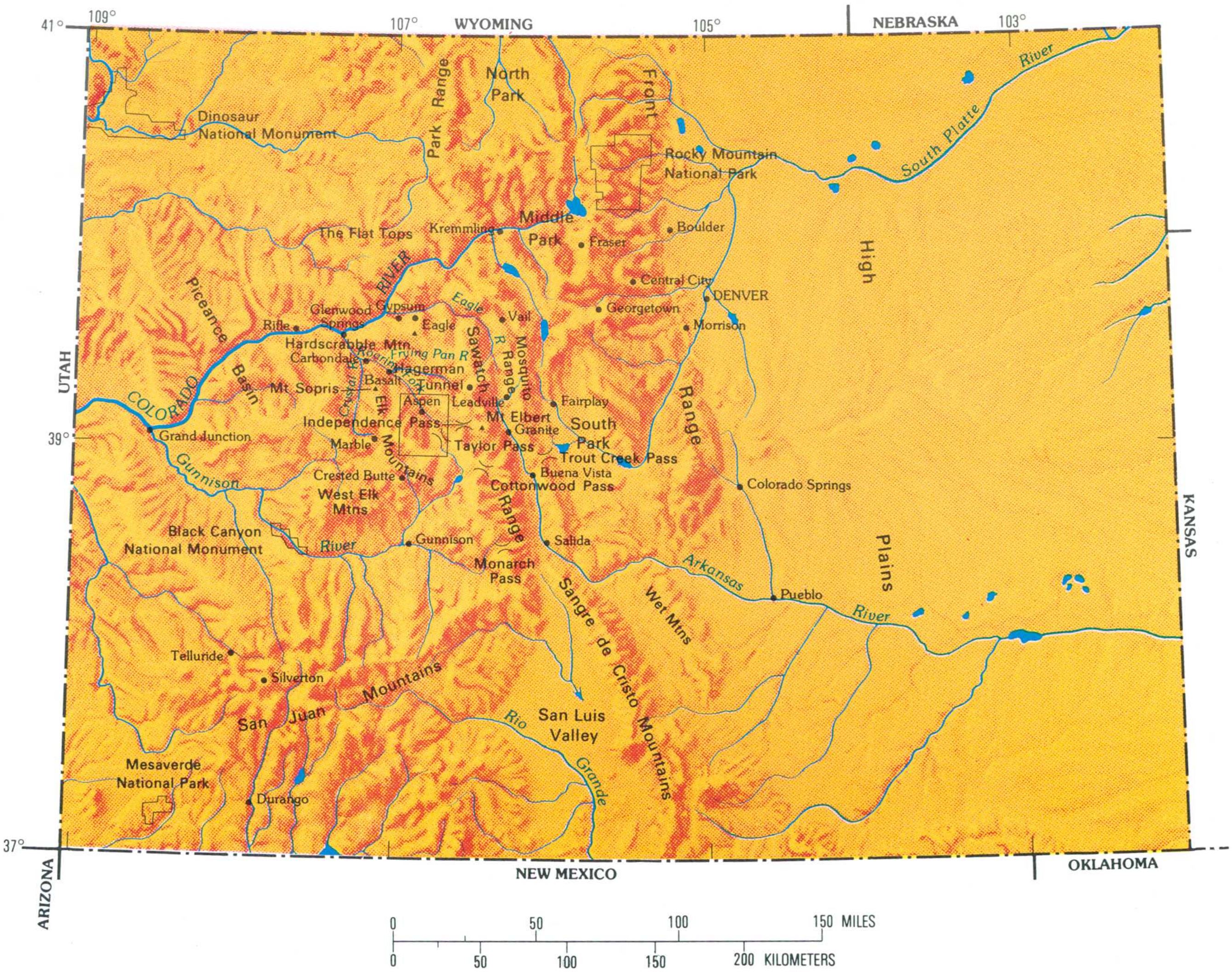


Figure 2. Map of Colorado showing mountain ranges and location of Aspen and other major features mentioned in the text. Outline around Aspen shows area of figure 3.

and scientific battle, both sides really lost. The decision was appealed, and the miners lost another valuable year preparing for a second trial before a compromise settlement was made. This legal quagmire halted normal development and production at the mines for 4 years.

About this same time the Denver and Rio Grande and the Colorado Midland Railroads, who were not interested in who won the legal hassle, raced to extend their systems to reap the Aspen business. The Denver and Rio Grande Railroad reached Aspen first—in October 1887. From a starting point at Red Cliff near the head of the Eagle River and west of the Continental Divide, construction crews frantically built a narrow gage line down the Eagle and Colorado Rivers to Glenwood Springs and then up the Roaring Fork valley to Aspen (fig. 4). Glenwood Canyon posed some trying engineering problems, but this route proved to be easier to follow than the shorter route pursued by the Colorado Midland, which reached Aspen several months later. That railroad built a standard gage line that began at Leadville and crossed the crest of the Sawatch Range in a short tunnel at 11,800 feet altitude, then followed the Fryingpan River to Basalt and turned up the Roaring Fork River to Aspen.

The Denver and Rio Grande, since converted to standard gage, still operates a branch line to Woody Creek, but the old roadbed into Aspen along the river was abandoned in 1969 and became a public trail for riding, fishing, and skiing. The Colorado Midland Railroad no longer exists, but parts of its former roadbed, which led to Aspen on about the present route of Colorado Highway 82, remain at the foot of West Aspen Mountain on the edge of town.

After the railroads arrived in 1887, Aspen had its greatest mining boom. In 1888, silver production increased

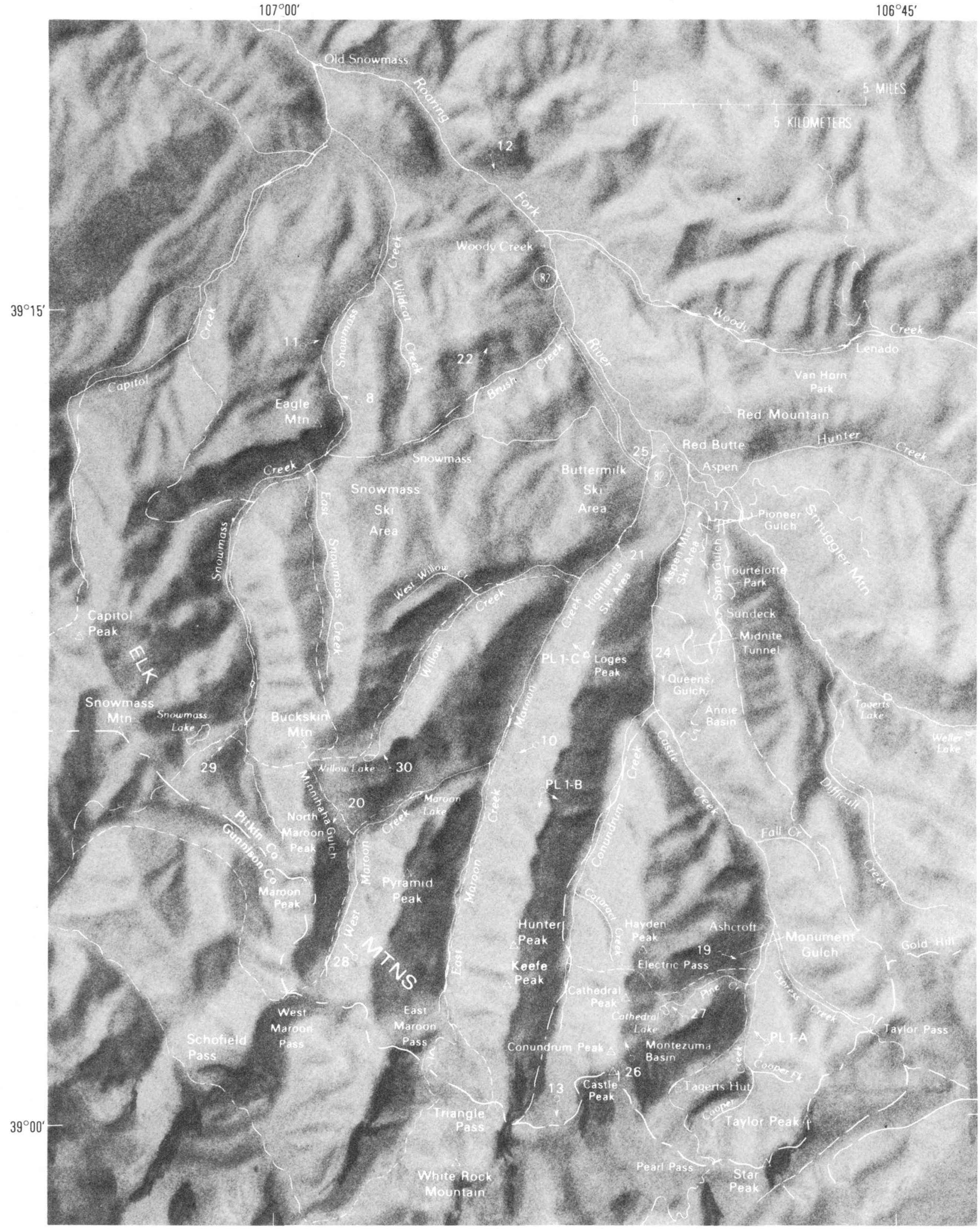


Figure 3. Map of Aspen region showing streams, peaks, settlements, roads, trails, and localities of photographs in this bulletin. Arrows point in direction of view. Numbers refer to figure numbers; p1 refers to panoramic views on plate 1*A*, *B*, and *C*.

Figure 4. Early trails and railroads leading to Aspen.

tenfold above the previous year; it reached a peak in 1892, when 8,256,467 ounces of silver were mined—worth more than $80 million at 1980 prices (fig. 6). In the prosperous early 1890's, Aspen was the principal city on the western slope of Colorado and must have bustled much as it does now, for it housed a reported population of 11,000—which equalled the number of both the permanent residents and the skiers at the height of the ski season in the late 1960's. The demonetization of silver in 1893 forced a precipitous decrease in the amount of ore mined, and only half as much silver was mined in 1895 as in 1892.

After 1900, mining continued but production value declined, even though lead and zinc contributed significantly to total production, especially during World War I (fig. 6). In the 1920's, metal production fluctuated greatly, and it reached a low point in the early 1930's. From 1928 to 1952 the Midnight Mine, which had its tunnel portal

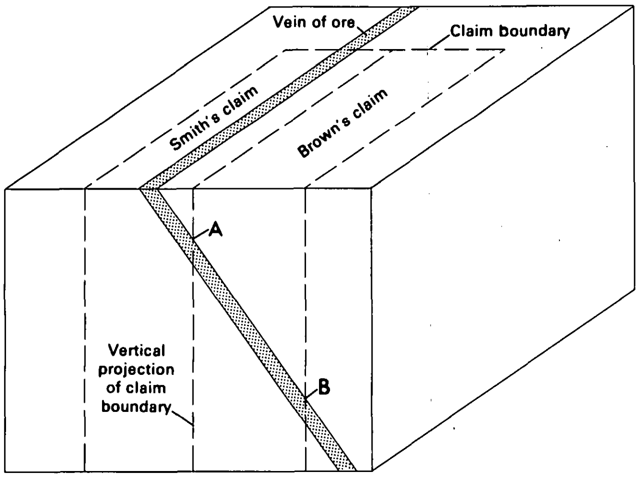


Figure 5. Block diagram showing issues at stake during mining litigation at Aspen. According to the Apex Law, Smith could mine the vein found on his claim down the dip as far as he could follow it beneath Brown's claim and any others, since Smith owned its outcrop, or apex. According to the law of vertical side-line boundaries, Smith could mine the vein only as far downdip as point *A*; Brown would own the ore in the vein beneath his claim and down the dip of the vein below point *A* to the place where the vein left the rock beneath his claim at point *B*.

and mill in Queens Gulch and its orebody under Annie Basin (fig. 3), steadily produced silver, lead, and zinc. The Midnight must have been one of the principal sources of employment for the small population of Aspen during the 1930's and 1940's.

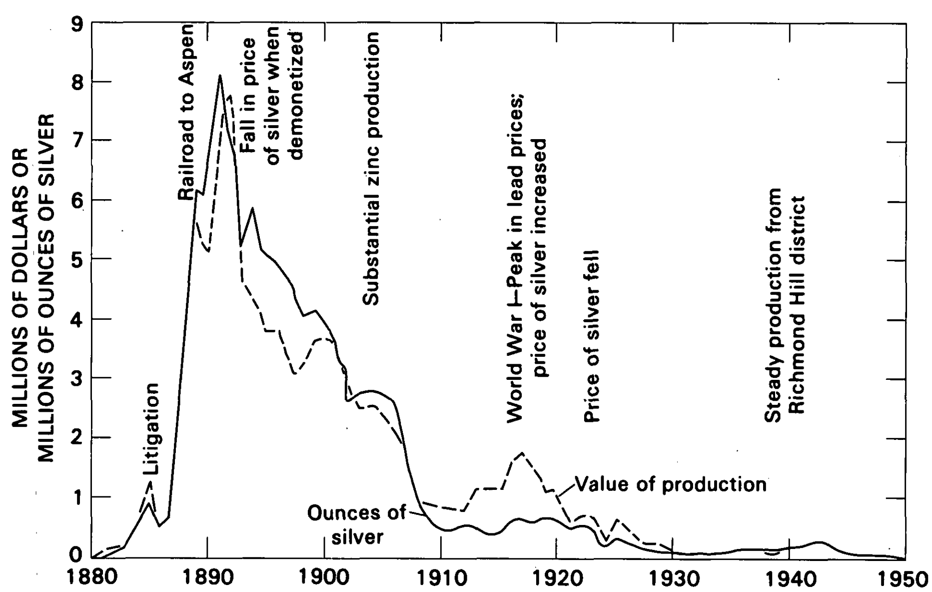
Very little silver, lead, or zinc has been mined in the area since 1952. However, from the 1960's to the present (1982), iron ore has been extracted during the summer months from a deposit at an altitude of more than 12,000 feet on the ridge north of Taylor Peak at the southeast head of the Castle Creek valley (fig. 3). In value and tonnage of rock moved, this operation compares favorably with that in the Aspen mining district during World War I. However, the mining revenues are small compared to the income from the new skiing and summer recreation industry that has burgeoned in Aspen since 1960.

Evidence of bygone mining activity still dots the modern landscape. On the north side of Aspen, waste dumps of the largest and richest mines—the Smuggler and Mollie Gibson (fig. 7)—are still recognizable, although recent housing construction has modified them. Mills that processed the ore also stood in that area; the most recent one was operated briefly in the 1960's in an attempt to extract ore minerals from those dumps. Farther north, on the slopes of Smuggler Mountain, the prominent dump just below the road is that of the J. C. Johnson Tunnel. On the south side of town the dump of the Durant Tunnel, which was a haulageway for ore during the later mining in Aspen Mountain, can be seen near Ute Avenue. Farther west at the edge of town lie the dumps of the Pride of Aspen (fig. 7).

The Aspen Mountain ski area occupies much of the old mining district. The upper chairlifts cross parts of Tourtelotte Park (fig. 7), where many mines and a small town briefly flourished in the late 1880's. The town declined only after an aerial tramway was built to carry ore from Tourtelotte Park to Aspen and workers from Aspen to the mines. When the ground is bare, one can see foundations of the towers and pieces of cable from that tramway in and near Spar Gulch. Ski-trail development has obliterated the mine dumps that used to dot Tourtelotte Park. But from the Bell Mountain chairlift, one can still see the dumps of the Bonnybel, Visino, and Little Percy mines on the west side of Spar Gulch. The road up the face of Aspen Mountain also dates from the mining era.

Other prominent signs of past mining activity are the dumps of the Little Annie and Midnight mines in Annie Basin (fig. 3), the dump of the Newman tunnel at

Figure 6. The growth and decline of mining in Aspen, 1880–1950. In reading this graph, remember that the dollar had a relatively constant value from 1880 to 1940, despite some fluctuations, and that the dollar value then was much greater than it is today.



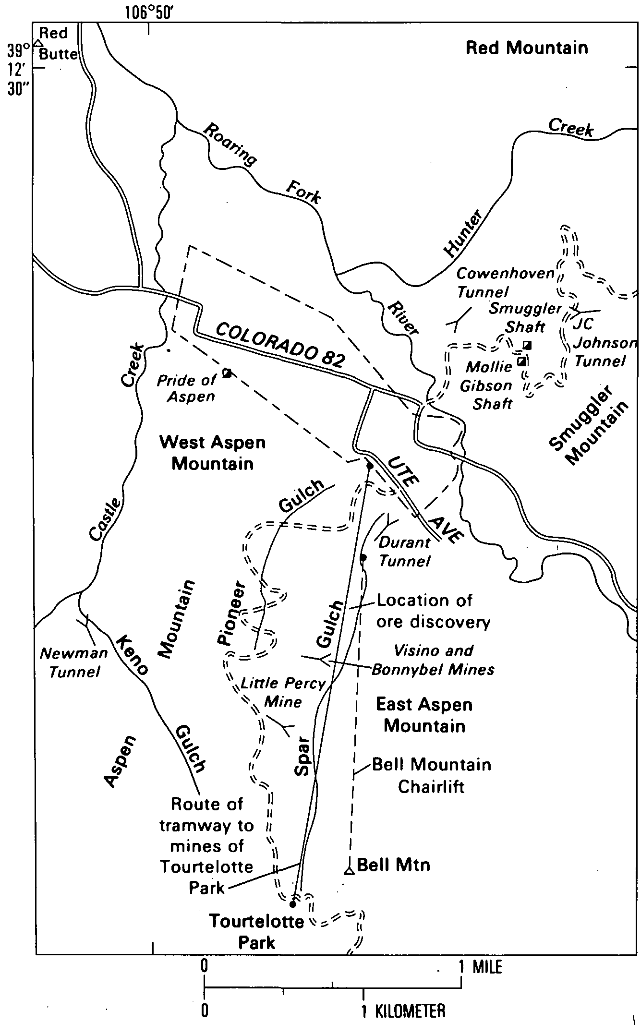


Figure 7. Location of some mines and other geographic features near Aspen.

the music school campus, and the dump of the Highland tunnel above the Castle Creek road opposite Conundrum Creek (fig. 7). The latter dump resulted from a relatively recent, though unsuccessful, mineral-exploration project in the 1960's.

Dumps from outlying prospects are visible in the high basins above Cathedral Lake, near the Tagert Hut and the head of Castle Creek, along the lower part of Express Creek, at Gold Hill, along East Maroon Creek and at its head, and off the trail between East Maroon and Triangle Passes. At the logging settlement of Lenado on Woody Creek, exploration conducted in the 1970's has added to dumps from earlier mining.

Some evidence of mining has disappeared. For example, photographs taken in the 1890's show much of Aspen Mountain stripped of timber, to provide wood for buildings, heating, smelting, and supports in the mines. Nowadays, the casual visitor might be unaware of the effect that mining had on the scenery, for these formerly denuded slopes support a forest of aspen, fir, and spruce—pleasing to the eye in all the seasons, but especially in the fall when the aspen leaves turn golden yellow.

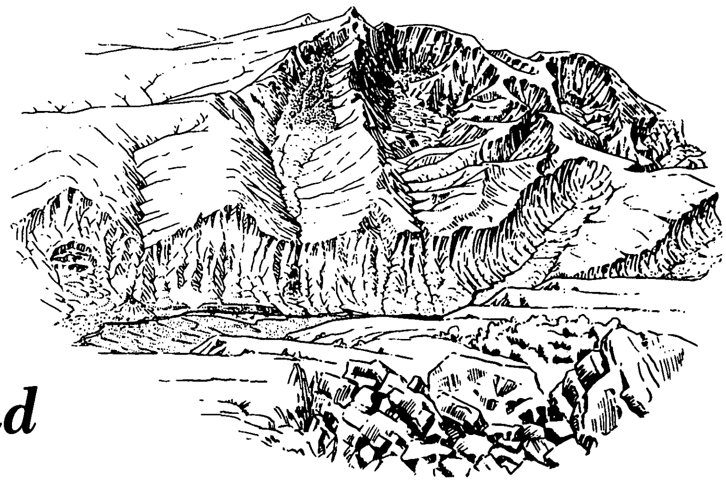
Not visible are the miles of tunnels that furnished access to orebodies or were driven in search of ore, and the cavities from which ore was mined. These workings form an underground labyrinth in a belt 500 to 2,000 feet wide, which extends from Hunter Creek to Tourtelotte Park, a distance of 3 miles (fig. 7). They pass beneath the Roaring Fork River at depths of 500 to 1,000 feet. The miners penetrated to a depth of about 2,500 feet beneath the shoulder of Smuggler Mountain, or about 1,300 feet lower than the city of Aspen. The longest single tunnel, the Cowenhoven Tunnel, extends more than 8,300 feet from Aspen to north of Hunter Creek. Most of the workings are either filled with water or collapsed.

Is mining near Aspen gone forever? Not necessarily. Low-grade deposits of lead, zinc, and silver are known to be present at Aspen. If the world's consumption of metals continues to rise and if we continue to lack facilities for recycling metals, these deposits will become more attractive economically. In the not-too-distant future—perhaps in several decades—the people of Aspen may face the revival of mining and the difficult decisions that revival will bring.

In the mining days, a few people used skis to traverse the mountains in the winter, and probably at times they used them for sport. In the 1930's, skiing in the United States became a recreational industry. In the later 1930's, attempts were made to develop skiing resorts in Aspen, but they were unsuccessful and were halted by World War II.

In 1946, the modern development of Aspen as a recreational and cultural center began. The Aspen Mountain ski area operated the first chairlift during the winter of 1947. The Aspen Music School and the Aspen Institute were established shortly thereafter. In the late 1950's, Buttermilk and Aspen Highlands ski areas were started. Growth was slow at first, but in the 1960's it snowballed. The ski area and planned resort of Snowmass-at-Aspen was created, and the first large condominium apartment buildings were constructed. This growth continues today. Tourists, campers, hikers, and climbers come in increasing numbers in the summer to enjoy the spectacular mountain scenery. So many have come that the U.S. Forest Service has been forced to control camping in many areas because of practical and esthetic considerations.

The core of this scenic area is the Maroon Bells–Snowmass Wilderness in the Elk Mountains southwest of Aspen. Many thousands first view this area closely from Maroon Lake at the head of the Maroon Creek road, one of the most scenic spots accessible by automobile in the southern Rocky Mountains. The scenery, recreational features, and cultural activities offered by the town of Aspen, although they can suffer a decline by improper use, will not be mined out as the rich silver deposits were.



The Story of the Land

The history and the present-day economy of Aspen are both inextricably tied to its geologic history. A century ago settlers came for silver, lead, and zinc; today visitors are lured by the silvery sparkle of new-fallen snow adorning towering peaks, the cheerful bubbling of a clear, cold stream rushing through a verdant valley, or the golden hue of autumn aspen leaves gracing an uncrowded mountain trail. The mineral treasures and recreational pleasures of this area did not just happen overnight. They both represent the net result of processes that have been at work since the Earth took form more than 4½ billion years ago.

In the Aspen area, as in any area, there are basically two geologic stories to be told. One is a story of great antiquity that is told by the rocks themselves—by their arrangement and composition. The other story is told by the shape of the land; it covers a rather short period of time by comparison, but its effect on the present scenery is every bit as profound as that of the bedrock story. Unlike the buried rock strata, landforms are conspicuous, and the story they relate—the "final chapter" of geologic history—is known with much greater certainty and in greater detail than the story concealed in the ancient rocks. Therefore, our account of Aspen's geologic past begins at the end.

Rushing Water and Tumbling Rock

In the Aspen area, where many craggy peaks and ridges rise to 13,000 and 14,000 feet above sea level, more than a mile above the valley bottoms, many of the processes that are even now sculpting that rugged beauty can be seen in action or in the results of recent events.

The evolution of the present landscape began in late Tertiary time—perhaps as much as 20 million years ago—with the general uplift of the entire Western United States. This uplift may still be in progress in many parts of the West, though its causes are complex and their details uncertain. Uplift was not uniform, and, consequently, blocks of land in some parts of the West (such as the San Luis Valley southeast of the Sawatch Range and many valleys in western Montana and Nevada) remained low or were dropped down relative to the adjacent mountains. Within 15 miles of Aspen (fig. 3) the uplift was uniform, and the valleys in this area were not formed by blocks of land remaining low. Instead, these valleys were carved by tributaries to the great Colorado River. These streams cut down as the land rose. The Colorado and its tributaries formed some of the most spectacular canyons in the world, such as the Grand Canyon, the Black Canyon of the Gunnison, and Glenwood Canyon. Most of this valley cutting in the plateaus west of the Rockies occurred more than 2 million years ago; but near the head of the drainage system, as in the Aspen region, the valleys were cut down considerably during the past 2 million years and are still being deepened today.

Where these streams have eroded the land, valley walls are steep and the terrain is rugged. But high on the ridges between the valleys the topography is much gentler. From the top of the lifts at Aspen Mountain, Aspen Highlands, and Snowmass ski areas, these flat-topped ridges stretch north and northwest as far as the eye can see (pl. 1,C). Their tops are generally 10,000 to 11,000 feet above sea level. These *interfluvial uplands*, as they are called, are the remnants of an old, gently rolling landscape that formed before the late Tertiary uplift and at an elevation much closer to sea level.

As this former landscape rose, forces of erosion immediately began to carve into it, cutting more and more deeply as uplift continued. Running water carved valleys; the freezing and thawing of water and ice, the wedging action of growing plants, and the weathering of minerals sent rocks tumbling down steep slopes and cliffs; and avalanches of loosened snow swept more rocks and soil toward the valley bottom. All these processes continue today. Through their action, bits and pieces of the solid mountains eventually reach the streams, where they are carried away by the rushing waters, and the highlands are cut apart and slowly but surely leveled. Of all these processes, gravity is the prime mover. Its effects are manifested in many ways—some very subtle, others spectacular or catastrophic.

The summer visitor to the high peaks can hear gravity at work—the rumble of rocks as they slide or fall from cliffs down to the slopes below. Probably more rocks fall in the spring than in any other season, because in spring the melting of snow during the day provides water that seeps into cracks and freezes at night. The expansion of the water during freezing widens the cracks bit by bit and eventually pries pieces of rock from the cliff. In places these loose, angular rocks accumulate below cliffs in deposits called *talus* (figs. 13, 20, 27, and 30). The larger the rock loosened from the cliff the farther it tumbles before coming to rest; consequently, larger fragments are found at the bottom of talus slopes.

For the high-mountain hiker, traveling across talus can be tiring and even dangerous if companions on the slope above are careless or if the hiker steps on a precariously perched boulder. Loose rock and talus constitute the major hazard to the climber on the Maroon Bells or Pyramid Peak. Although the mountaineer encounters the largest expanses of talus, the automobile traveler may see patches of talus on the side of the canyon of Maroon Creek and on the south side of Maroon Lake.

In winter, tremendous avalanches of snow cascade from the peaks and high ridges, carrying rocks and debris with them. In many places in the high mountain valleys, avalanches frequently pour down the cliffs and steep slopes into the timber and form a track swept clean of trees. A number of avalanche tracks scar the sides of the Maroon and Conundrum Creek valleys. Several avalanche tracks cross the Maroon Creek road, from which trees and rocks, carried down by the torrents of snow, must be cleared before the road is opened for summer use. Tracks used infrequently by avalanches may have dense stands of small aspen in them (pl. 1, *A* and *B*). An unusually large avalanche, called a *climax avalanche*, may widen an avalanche track or make a new one by literally mowing down and tearing up mature timber. Such avalanches in the Aspen area may flow as far as 1½ miles from the ridge crests to the valley bottoms and up onto the opposite valley wall.

Besides their harsh effect on the landscape, avalanches also pose dangers to people and property. Even small avalanches, which may move no rocks or vegetation, are hazardous to people. Fatal avalanches dot the history of the Aspen area from one in 1884 that wiped out a cabin full of miners on Conundrum Creek to several in recent years that have claimed the lives of skiers.

The crystal-clear streams around Aspen are a great natural attraction of the region during the summer and winter seasons, when most visitors are present. However, during the spring runoff, which reaches its height in late May or early June, the streams are full of rushing, muddy water carrying billions of small grains of minerals from the rocks and soils they drain. The fast-moving water even shifts and rolls large boulders in the streambed. Even in the summer, uncommonly heavy rain may make streams high and muddy.

These same rains can trigger landslides and mudflows that contribute to the erosion of the rocks. They can be catastrophic, and their effects are very visible. In August 1874, W. H. Holmes observed one of these heavy summer rains in the Crystal River valley (then called Rock Creek):

> On the 29th a rain-storm had set in, and everything was now wet, thoroughly saturated. Muddy torrents poured down the upper slopes and dashed over the cliffs into the valley. Avalanches of wet earth, carrying many rocks and trees, formed near the summits and came roaring down, discharging their great masses of debris into the river, and tearing out such gorges in the alluvial bottom as to make travel about impossible.

In 1956, a large landslide and muflow occurred on the west side of the Snowmass Creek valley (fig. 8). A lateral moraine became saturated, probably from a break in an irrigation ditch close to the upper edge of the moraine. Water filled the spaces between the grains of sand and silt in the moraine, overcoming friction between the grains and adding to the weight of the mass. Cohesion was lost, and the entire mass slumped down the steep slope of the valley side; parts of the mass completely came apart and flowed down across the valley bottom, obliterating the road. A spectacular view of this landslide can be seen from the Snowmass Creek road.

A much less spectacular event in 1965 caused minor damage in the city of Aspen. Heavy rains on Aspen Mountain caused mud to flow down Pioneer Gulch into town. The flow was small and its effects are not obvious today.

Heavy rains, mudflows, landslides, and avalanches were all yearly occurrences in the Aspen area long before man arrived, and all these processes are active today. This year, the Roaring Fork will carry away many tons of rock and soil from the region, as it has done for millions of years. However, one major erosional process has not been active in recent years, even though its effect on the high country overshadows those of all other types of erosion. The rugged landforms of the Aspen region speak forcefully of a time when great, moving masses of ice filled the high mountain valleys.

Figure 8. Moraines, landslides, and mudflow on Snowmass Creek viewed northwest from ridge between Snowmass and Wildcat Creeks. All the foreground and most of the far side of the valley is glacial moraine, plastered on the valley sides by a glacier that once filled the valley to a depth of about 600 feet; the glacier moved from left to right downvalley. The large, fresh landslide and mudflow in the center carried a large segment of the moraine down onto the valley floor. They were probably caused by the soaking of the moraine and underlying shale from a break in an irrigation ditch crossing the meadow on top of the moraine. The fan-shaped, tree-covered hummocky area to the left of the new slide is an older landslide of Cretaceous shale that slumped off the valley wall. Photograph taken in 1968.

The Pleistocene Epoch—Rivers of Ice Sculpture the Land

The world has not always been as warm as it is now, or as cold. In fact, through most of geologic time, world temperatures were higher than they are today. But for the past 2 million years or so this has not been true: during this period the world has usually been colder, and sometimes much colder, than it is today. The causes of this global cooling are not well understood—there are as many theories as there are climatologists—but its effects are well documented.

Glacial ice accumulated during that time in the subarctic areas of the Earth, and icy lobes thousands of feet thick pushed south across Europe, Asia, and North America. In the Eastern United States, the continental ice sheets extended as far south as New Jersey and southern Ohio. But in the West this glacial advance halted in northern Montana, so the great continental icecap never reached the Aspen area. Instead, the colder climate then prevailing gave birth to smaller alpine glaciers in the Colorado high country.

Even though the Colorado glaciers were not continental in scale, they were impressive. At times the glacier in the Roaring Fork valley extended 20 miles from the crest of the Sawatch Range downstream to Aspen and beyond (fig. 9); in places it was more than 2 miles wide and 1,500 feet thick. Elsewhere in Colorado, some glaciers were twice this size.

Everywhere these rivers of ice flowed (fig. 9), they had a spectacular effect on the landscape. The pointed peaks, sharp ridges, and steep-walled basins of the Sawatch Range and the Elk Mountains are reminiscent of those in the Swiss Alps. Here, as in Switzerland, these landforms were carved by glacial ice.

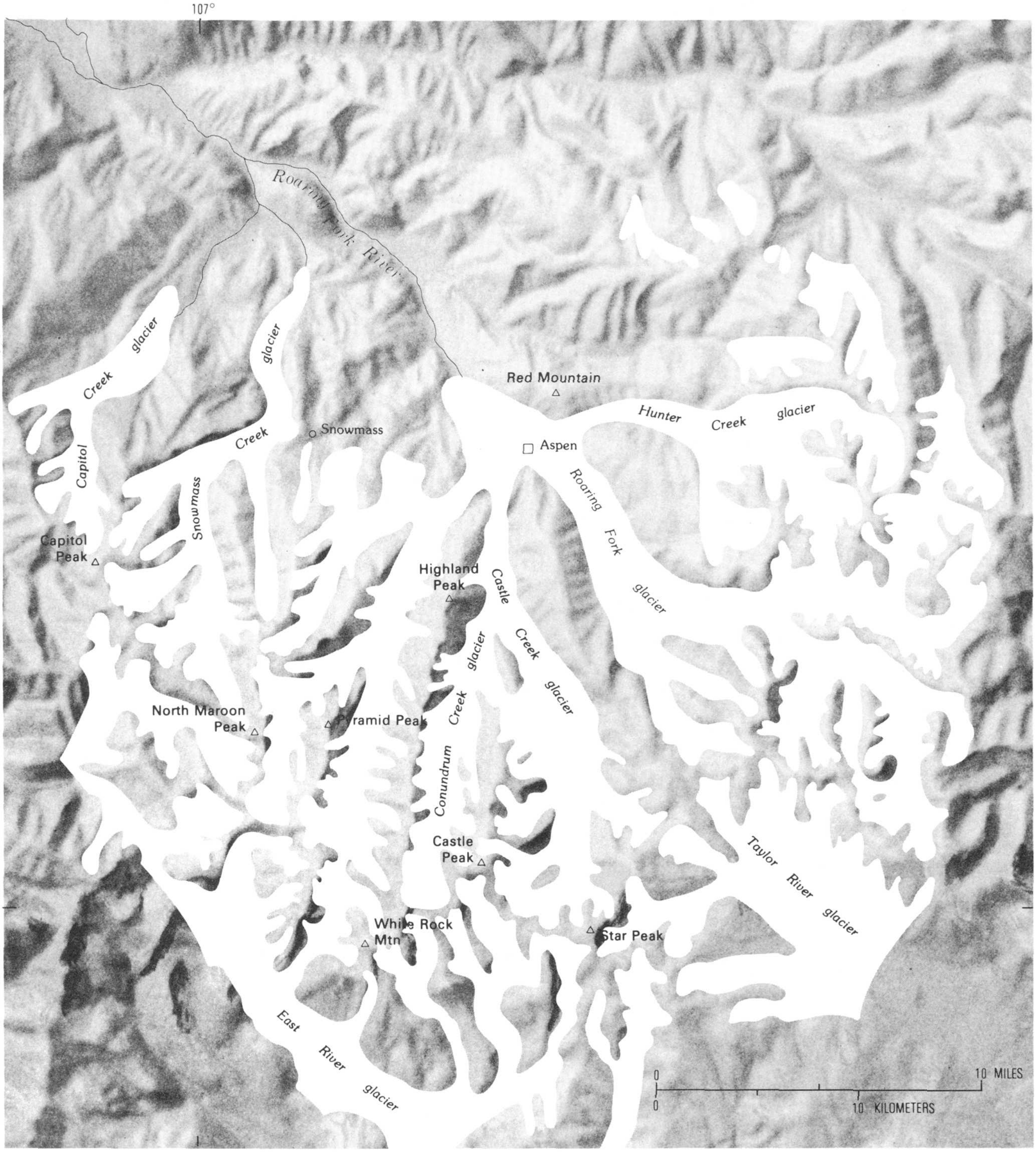


Figure 9. Extent of glaciers in the Aspen region during one late Pleistocene glacial maximum.

The onslaught of the ice was not continuous near Aspen or anywhere in the world. In the last 2 million years or so, there were at least four major advances and retreats, and probably many more. Each of these major glacial periods comprised several minor advances and retreats. During some of the earlier advances the glacier from the Roaring Fork coalesced with those from the valleys of Maroon and Castle Creeks and flowed a short distance down the Roaring Fork valley. The most recent advance that reached down the Roaring Fork valley almost to Aspen occurred between 15,000 and 20,000 years ago. Glaciers from the valleys of Maroon and Castle

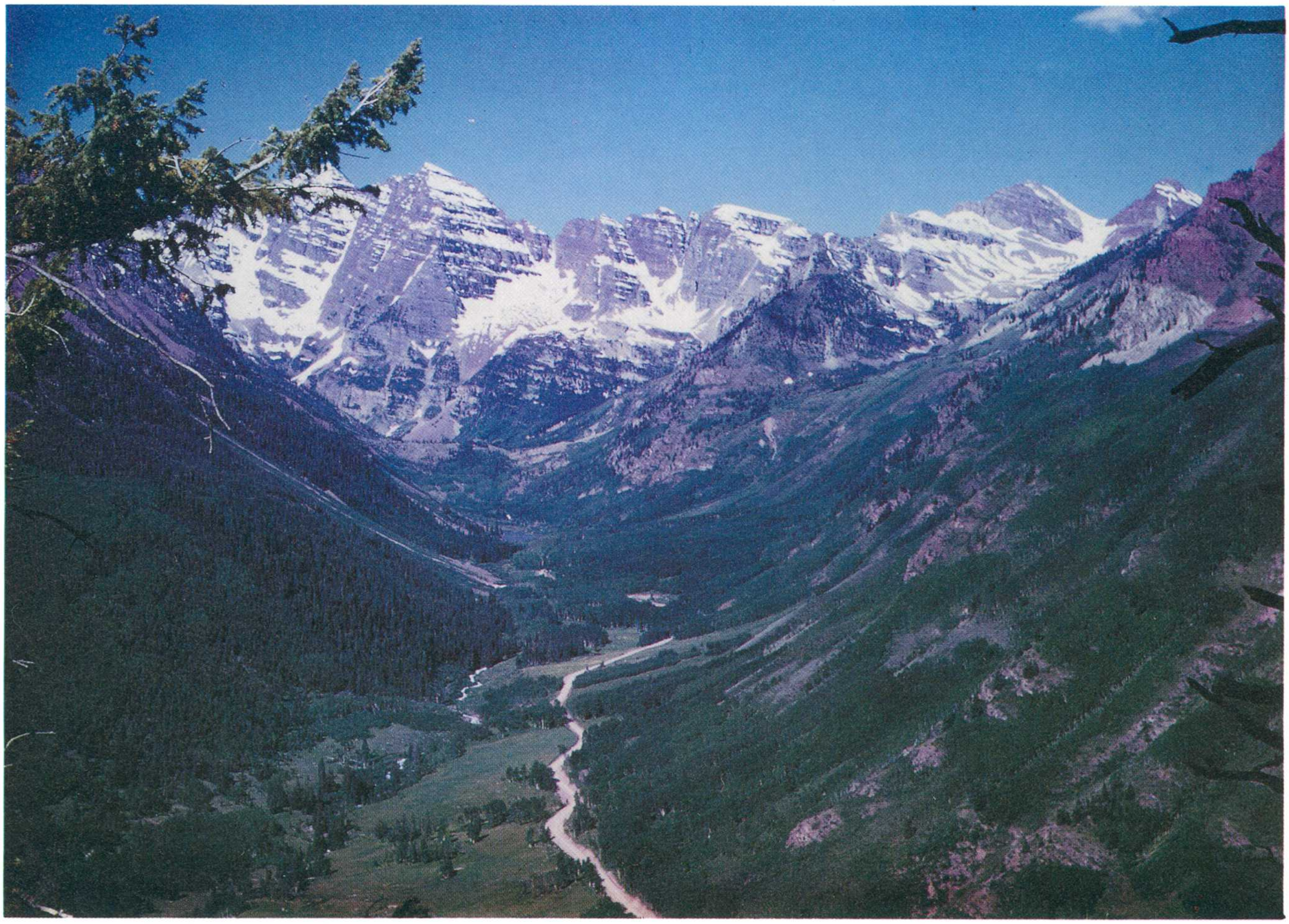


Figure 10. The Maroon Bells—the most popular, most photographed scenic attraction in central Colorado—were carved by glacial ice out of reddish-gray sandstone and siltstone of the Maroon Formation. (See p.35). The valley of West Maroon Creek, in the foreground, displays the U-shaped profile typical of glaciated valleys. View looking southwest. The Maroon Bells is the collective name for the two high peaks on the left. The left-hand one is officially known as Maroon Peak, but many call it South Maroon Peak. The right-hand one is North Maroon Peak.

Creeks coalesced and stopped on the threshold of the Roaring Fork valley during that advance. Since that time, at least three minor readvances left their deposits upstream from Aspen in all three of these valleys.

Glaciers form when winter snowfall exceeds summer melting over a period of many years. The accumulated snow compacts and recrystallizes to form *firn*, a coarse-grained snow composed of ice particles with spaces between the particles. Additional accumulation of snow causes further compaction, and the firn recrystallizes to form ice, in which no space exists between individual crystals. Ice flows downhill in a plastic manner under the influence of gravity. As the ice flows, it plucks and grinds rocks beneath it and transports debris from the valley walls above it.

When climatic conditions were cooler than they are at present, glaciers formed in the heads of small valleys near the crests of the high ridges south and east of Aspen. Over many thousands of years they gouged out these valley heads into deep, bowl-shaped basins called *cirques*, and they plucked their way back into the ridges. When glaciers pluck their way into a high mountain from three or more sides, they leave a sharp peak between them known as a *matterhorn* after the famous Swiss peak. Examples of peaks near Aspen formed this way are Castle, Pyramid, and Maroon Peaks (fig. 10). Here, the headward erosion of the glaciers did not go far enough to produce nearly as spectacular an effect as it did on the Matterhorn, but the process was similar. Two glaciers eroding headward from opposite sides of a ridge produce a sharp, serrated ridge called an *arête* where the two cirques meet. These processes of glacial erosion give the high country of the Elk Mountains its Alpine aspect (pl. 1, *A* and *B*, skyline and ridges; figs. 10, 20, and 27).

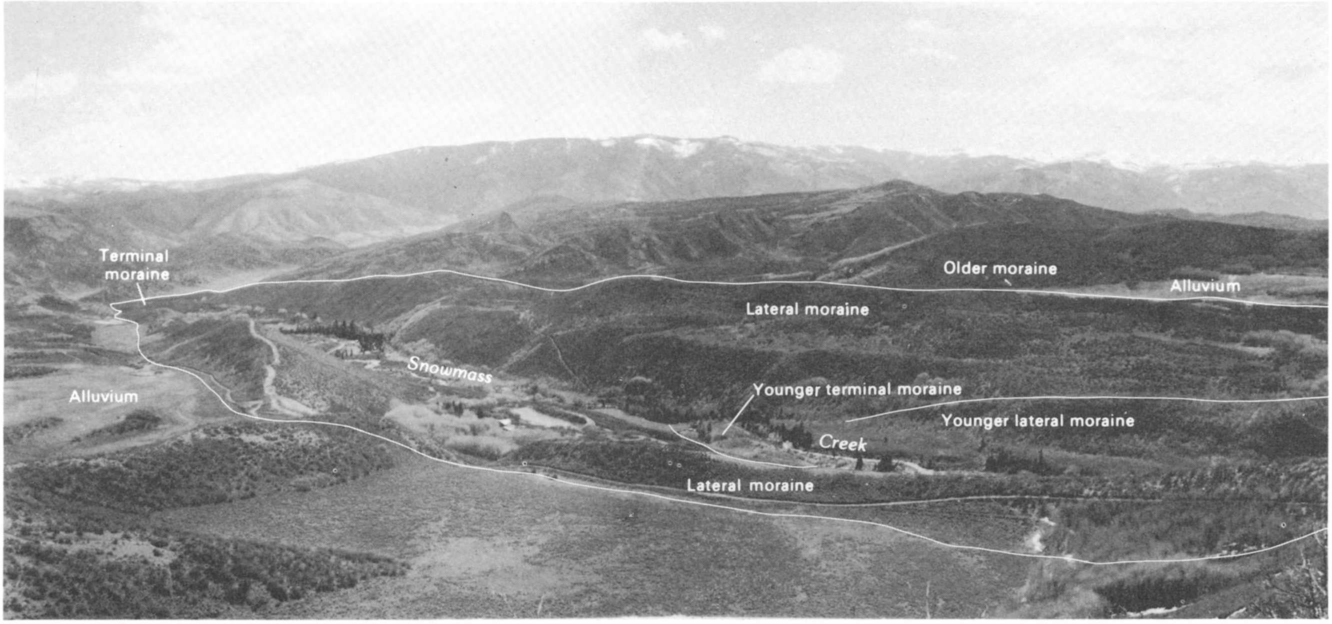


Figure 11. Complex of moraines in Snowmass Creek valley near end of Snowmass Creek glacier, viewed northeast from small hill north of Hunter Creek. The lateral moraine in the foreground, from the glacier that advanced the farthest in the last 150,000 years, can be traced downvalley to a terminal moraine in the brushy area where the valley begins to bend. The gently sloping area in the foreground and other areas like it downvalley were formed by mud that washed out of the adjacent hills and collected behind the newly made lateral moraine when ice still occupied the valley. Small ridges across the creek on the right are smaller, younger lateral moraines. Photo taken in 1968.

The glaciers were unyielding as they flowed downstream from their cirques. Any irregularities or protuberances on the valley walls were ground off and carried away, as were any loose rocks, dirt, or plant life the icy tongue encountered. This load of rubble then became part of the glacier's arsenal and contributed to the scraping and scouring of the rock surface under the ice. On the floors of glacial valleys, long parallel grooves called *striations* have been cut into the bedrock where jagged boulders were dragged across by the ice. As the glaciers pushed and scraped their way downstream, the valleys were deepened, broadened, and straightened. Eventually, they assumed the U-shaped profile that is characteristic of glacial valleys (pl. 1, *A* and *B;* fig. 10).

During the more recent glacial episodes, the glaciers in the main canyons south and east of Aspen were 1,000–1,500 feet thick. They were bigger and, therefore, cut deeper than those in the side valleys. Consequently, when the ice retreated, the tributary valleys were left at a higher level—"hanging" as much as 1,000–1,500 feet above the main valleys: the main valleys were deepened that much by glacial erosion. Good examples of such *hanging valleys* are seen where Difficult Creek joins the Roaring Fork River, where Cataract Creek joins Conundrum Creek (pl. 1, *B*), and where valleys south and west of Maroon Lake join West Maroon Creek. Many small cascades or waterfalls form at the ends of hanging valleys recently exposed by a glacial retreat.

At the mouth of a hanging valley, the water tumbling down the steep wall of the main valley suddenly slows upon reaching the flat valley floor, and much of the sand and silt it has carried down from above settles out at that point. During periods of high water, even boulders may be added to the pile. The resulting landform is conical in shape and is called an *alluvial fan.* Such fans are conspicuous on both sides of the Roaring Fork valley, a few miles upstream from Aspen.

The rubble that glaciers carry consists of both large and small rock fragments. The largest fragments may be boulders several feet in diameter; the smallest fragments are the size of the silt particles typically carried by a muddy stream. As the glacier inches down the valley, it encounters higher temperatures and begins to melt. The advance continues until the front of the glacier is melting as fast as new ice is supplied from above; then the glacier stops advancing, but it keeps moving internally, bringing more rock fragments from upvalley and dropping them at the point where the ice disappears. The rubble forms a bouldery ridge or a series of low hills called a *moraine* (fig. 11). Moraines deposited at the end of a glacier are *end moraines;* those deposited along the sides of a glacier, below the main source of the ice, are *lateral moraines.*

The moraines deposited during major glacial episodes are best developed in the Roaring Fork valley and

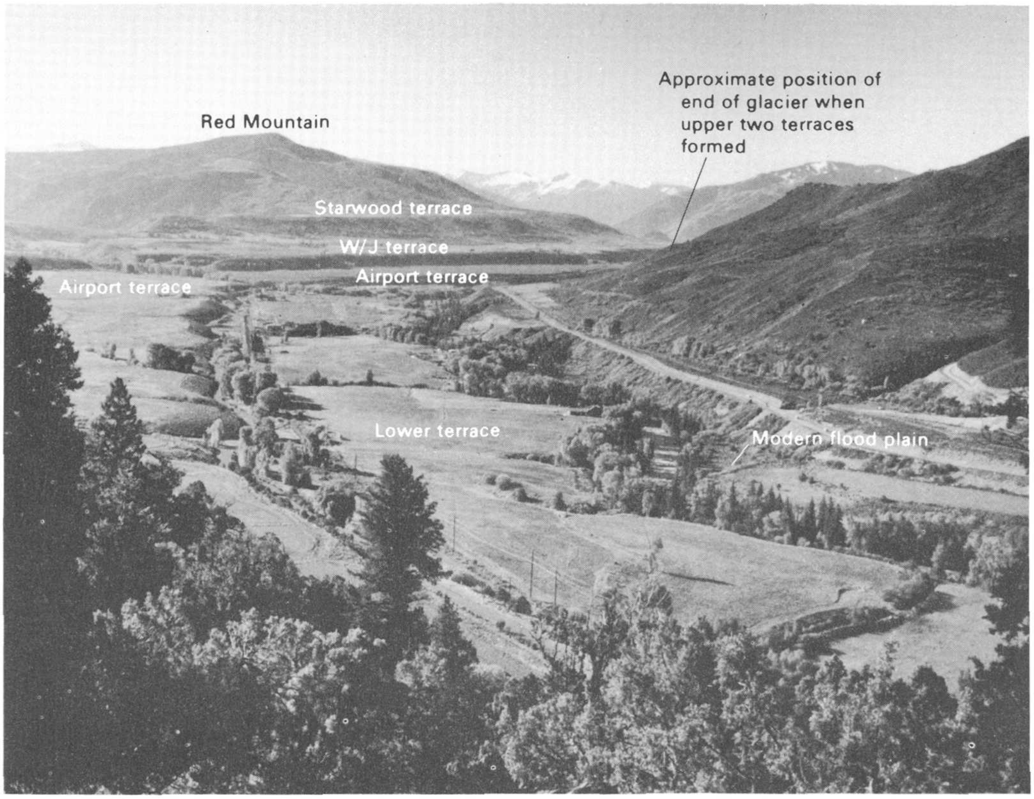


Figure 12. Terraces of Pleistocene glacial outwash in the Roaring Fork valley downstream from Aspen, viewed upvalley from lower part of basalt-capped hill northwest of Woody Creek. Glaciers carried much debris to their ends near Aspen. There, large volumes of glacial meltwater washed the debris downvalley, where it was deposited, partly filling the valley. The river cut down into this valley fill and eroded part of it during nonglacial times, such as the present. Debris from younger glaciers again filled the valley, but not to as high a level, because the valley had become slightly deeper and the glaciers were somewhat smaller. The lowest and youngest terrace in the valley bottom is poorly developed upstream near Aspen. It may be related to a moraine several miles above Aspen, or it may have formed in postglacial time. The city of Aspen is built on the Airport terrace. A narrow, modern flood plain adjoins the river.

in the lower part of the Snowmass Creek valley (fig. 11). In the Roaring Fork valley one moraine forms the dam that holds in Weller Lake; another forms a noticeable step in the valley along Colorado Highway 82 west of Tagerts Lake; still another forms the low wooded hills in the valley just east of the city of Aspen.

At the snout of the glacier, meltwater rushing away from the ice picks up some of the rock fragments and deposits them in the valley directly below the glacier. The material deposited is called *outwash* gravel. After the glacier melts back, the river erodes a valley into the gravel, and so the upper surface of the outwash remains as a *terrace* many feet above the river.

Outwash terraces form the flat valley bottom on which the city of Aspen and the airport are built (fig. 12; pl. 1*C*). Gravels in higher terraces were deposited during earlier glacial advances when the end of the glacier came a little farther down the valley. One such terrace, which stands about 160 feet above the Airport terrace, is occupied by the main buildings of the W/J Ranch. A low hill just east of the airport is a remnant of an older end moraine that was deposited at the same time as the W/J terrace. An even higher and older terrace is that of the Starwood subdivision.

The terraces and moraines in the Roaring Fork valley, for the most part, date from the latter half of the glacial epoch. The scouring tongues of ice and the rushing torrents of meltwater have destroyed most evidence of earlier glaciations. Nevertheless, the top of Red Mountain, 2,000 feet above the Roaring Fork, is covered by an ill-sorted deposit of rock fragments much like those that compose the glacial moraines in the valley below. Unlike those moraines, though, the Red Mountain deposit spreads over a broad area, as might be expected if it were left by a glacier that was not confined to a narrow valley.

Ten miles downstream, the Roaring Fork River winds through a steep-walled canyon near the town of Snowmass. A deposit resembling outwash gravel has been found on a low divide about 3 miles southwest of Snowmass, about 1,500 feet above the present level of the river. Evidently, when the earliest glaciers crept down the Roaring Fork valley—perhaps 2 million years ago—the valley floor was 1,500 to 2,000 feet higher than it is now and the river flowed across that low divide, as Snowmass canyon did not yet exist. It is quite possible that the gravel on the low divide is outwash from the glacier that left its moraine on Red Mountain.

Most of the glaciers disappeared from the Colorado high country between 12,000 and 10,000 years ago. Yet, at the heads of many mountain valleys near Aspen, in the bottoms of old cirques, lie tongue-shaped masses of rock fragments that resemble ice glaciers and that are known to move imperceptibly (figs. 13 and 27). These are *rock glaciers*, and, in fact, some of them do conceal small bodies of moving ice, but no ice is visible at the surface. The daily cycle of freezing and thawing cuts into the walls of the cirques high above the rock glaciers and breaks loose a large supply of angular rock fragments. These fragments tumble down the cirque walls and are carried down the cirque floor in and on the glacier. Many of the fragments are several feet or more in diameter, so hiking across a rock glacier may involve strenuous boulder-hopping. Two of the rock glaciers, one on the Maroon Bells and one on Pyramid Peak, are carrying rocks downvalley at the rate of a foot or two a year. These glaciers are about a 2-hour hike from the end of the road at Maroon Lake. Just north of Pearl Pass the jeep trail crosses a rock glacier, but whether that one is moving, or how much, is not known. Other rock glaciers, which are covered with forest or tundra vegetation, lack steep fronts and probably are not active.

Studies on Mount Sopris, 20 miles west of Aspen, by P. W. Birkeland of the University of Colorado, show that the large rock glaciers there may have formed before the warm period 7,000 years ago from the remnants of the last great ice glaciers. Some of the large rock glaciers near Aspen resemble those on Mount Sopris and are probably as old. During a cool period that reached its maximum 100 to 300 years ago, a few glaciers formed and deposited moraines in Montezuma Basin at the head of Castle Creek and in a small cirque northwest of there (fig. 26). Rock glaciers probably became more active at that time.

Figure 13. Tongue-shaped body of rock fragments in a rock glacier in cirque at the head of Conundrum Creek. The rock glacier is more than 40 feet thick. Note that the steep margin shows fewer large blocks than does the upper surface. The margin is so steep that many of the rocks there fall down the slope in small rockslides. A rock glacier with such an active margin is probably advancing, though very slowly. Beneath the surface rock the space between the blocks may be filled with ice. Solid glacial ice may underlie the rock in places, especially at the upper margin near the cirque wall. Much talus lies on the steep slope above the rock glacier and in the left foreground. View looking southeast.

In general, though, the past 10,000 years has been a time of moderate temperatures; the great rivers of ice have been absent from the high country for at least that long. They will return—most geologists and climatologists agree on that—but no one knows whether that next advance will begin next year or 10,000 years from now. In the meantime the forces of erosion are not dormant. The U-shaped profiles of the glacial valleys are now disguised in many places by landslides, alluvial fans, and accumulations of talus; and modern streams have already cut deep gorges in the outwash terraces and are once again assaulting the underlying bedrock. Millimeter by millimeter, the Rockies are being leveled.

The Story of the Rocks

Ages ago, long before the first glaciers formed in the mountains near Aspen, the rocks of this region were already unimaginably old. Indeed, the oldest rocks in the area may be a thousand times older than the glacial rubble atop Red Mountain. The twisted and fractured layers of rock near Aspen record about 1.7 billion years of Earth history (fig. 14); but the record is not clear, and its interpretation requires careful observation and a few basic understandings.

Deciphering the Story

All rocks, including those near Aspen, originally formed in one of two ways: they either compacted from loose sediment or solidified from hot flowing magma. The loose silt, sand, and pebbles that compact to make *sedimentary rock* could be deposited by water in the ocean, a lake, or a stream, or by wind on dry land. The hot magma that creates *igneous rock* rises from the depths of the Earth, and it may break through the surface to form a volcano, or it may cool and solidify below the surface.

Whatever the circumstances of a rock's birth, those conditions are reflected in the composition and character of the rock. However, if a rock is subjected to intense heat or pressure its characteristics can change; it is then called a *metamorphic rock*, whether its origin was igneous or sedimentary. Through careful study of a rock's characteristics, we can reconstruct the general environment of its origin and, for a metamorphic rock, can draw some conclusions about its history.

However, the rocks near Aspen reflect a wide variety of original environments—from ocean bottoms to dry deserts—and we cannot begin to piece together a coherent geologic history until we know *when* these rocks formed, and in what sequence. For the many layers of sedimentary rock in the area, the depositional sequence and the *relative* ages can be determined with little difficulty.

Most sedimentary rocks are deposited as thin blankets that may cover thousands of square miles, although they may be only a few tens or a few hundreds of feet thick. Obviously, each of these rock layers is deposited on a surface of older rock, and any sediments that subsequently cover it will be younger. An extensive sedimentary layer cannot be deposited underneath an older stratum! (As we shall see, this is not necessarily true for igneous rock.) The Danish physician Nicolaus Steno recognized these simple facts more than 300 years ago, and concluded that the higher sedimentary strata in a rock sequence should be successively younger, *if the sequence is in its original position.*

Unfortunately, a perfect, unbroken sequence that extends from the oldest rocks to the youngest has not been found anywhere in the world. Forces within the Earth elevate its crust so that it stands high enough that gravity and running water take material away. Deposition of the rock sequence is interrupted. Violent movements of the crust turn the layers of rock up, and, in places, turn them upside down, break them, and push one layer across another, as has happened locally in the Aspen area.

Cemented among the grains of sand and silt in sedimentary rocks are the fossil remains of plants and animals that lived and died at the time the sediments forming these rocks were deposited. Shortly before 1800, the English engineer William Smith discovered that these fossils differed from one bed of rock to the next. In fact, he found that fossils in the same bed a hundred miles apart would be nearly identical, whereas those just a few feet above or below that bed would be somewhat different. In time it was learned that fossils of the same age from opposite sides of the globe are more similar to each other than are fossils of slightly different ages from the same area. This realization makes it possible to correlate the sedimentary rocks near Aspen with those in other areas and to assign them to their proper relative age, even though they do not form an uninterrupted sequence.

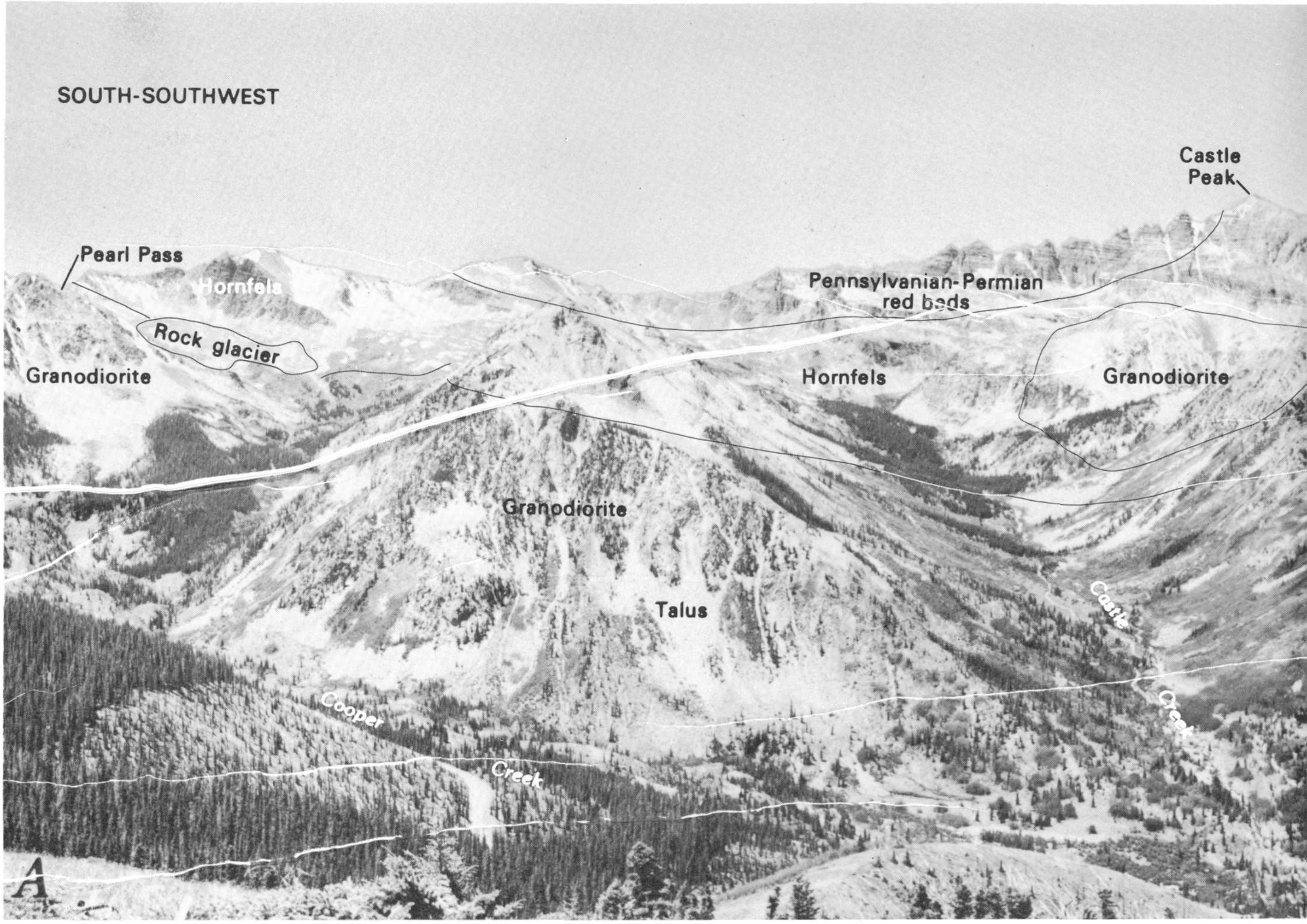


Plate 1A (above). Panorama from Castle Creek–Express Creek ridge showing White Rock Pluton, composed of middle Tertiary granodiorite, and its roof of upper Paleozoic red beds and hornfels of the Maroon Formation. The granodiorite contact is nearly parallel with the conspicuous bedding in the Maroon Formation near the right side of the picture, but it cuts the bedding below Castle Peak. Hornfels beds are clearly offset by a pair of faults to the left of Cathedral Peak. These faults probably formed in middle Tertiary time during intrusion of the granodiorite. Straight U-shaped valleys sculptured by glacial erosion are somewhat filled in by talus that fell and slid down the valley sides after the glaciers melted. Avalanche tracks extend downward from the sparse stands of conifers high on the sides of the ridges. Recently used tracks are grass covered; older tracks contain bushes and small aspens. The road near Castle Creek leads to Pearl Pass and Montezuma Basin. The road in the left foreground goes to Pitkin Iron Corporation Mine.

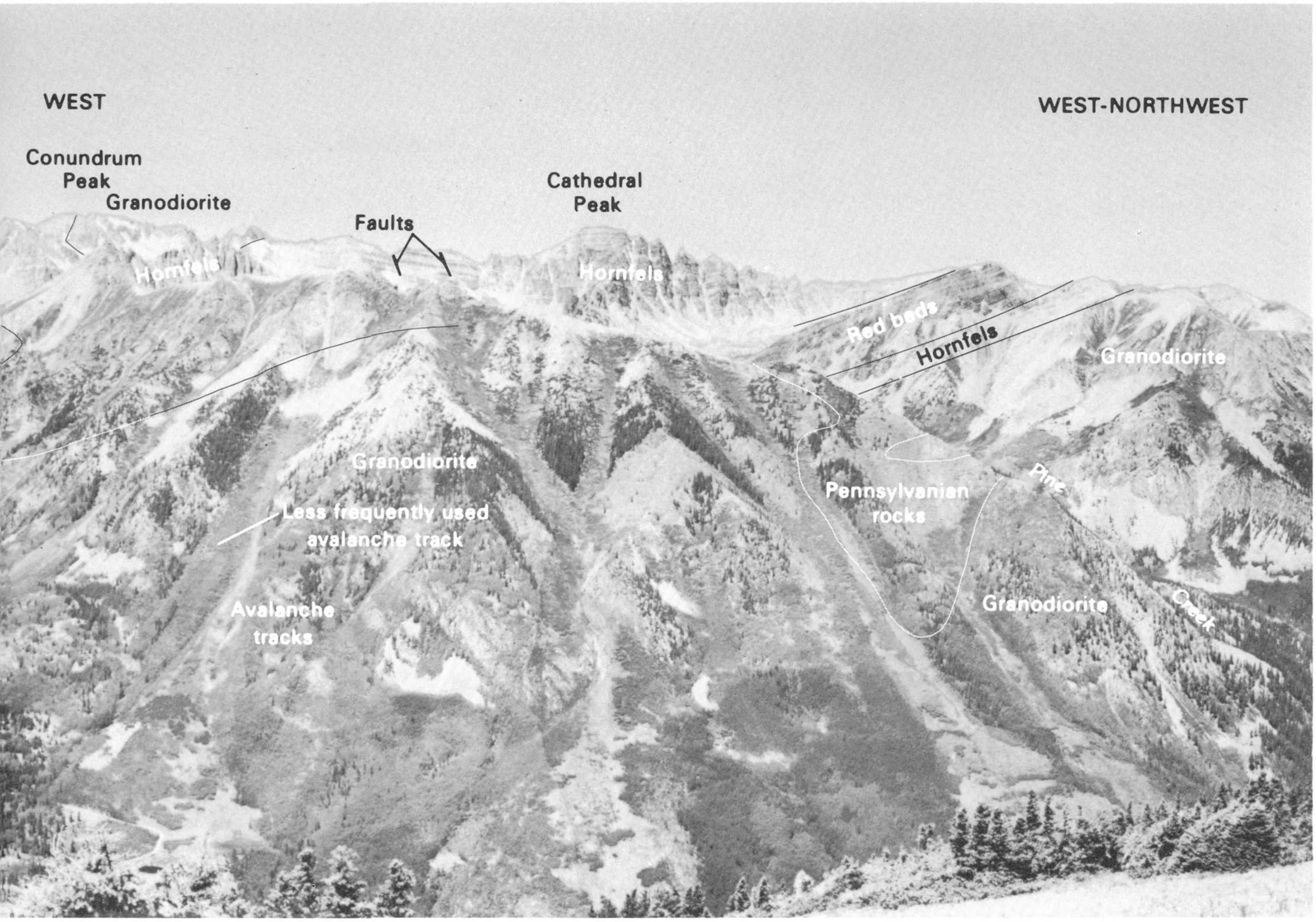


Plate 1B (on following pages). Panorama east to south up Conundrum Creek valley from ridge between East Maroon and Conundrum Creeks. The U-shaped profile of the valley was gouged by glaciers that filled the main valley about to the edge of the timber in the middle of the picture. The sharp ridge on the right is an arête separating two cirque basins that are tributary to the major valleys. The main glacier of Conundrum Creek gouged out its valley much more deeply than did the smaller glacier of Cataract Creek. Hence the Cataract Creek valley was left hanging above the main valley, and the lowest part of Cataract Creek now plunges steeply. Large areas of talus and two rock glaciers are visible. Numerous stripes devoid of trees below timberline are avalanche tracks. The clearing in the center remains from the prospecting era when trees were cut to build cabins and to furnish fuel for heating and cooking and for a steam engine that was used at a nearby mine. ➤

Plate 1C (on following pages). Panorama from west to north from the top of the Aspen Highlands ski area (Loges Peak), showing faulted Upper Paleozoic and Mesozoic rocks on the south flank of the Roaring Fork syncline, and part of the Castle Creek fault zone. Heavy lines are faults; lighter lines are contacts between formations. K=Cretaceous sandstone, J=Jurassic claystone, sandstone, and limestone, ŦR=Triassic red beds, ŦR P=Triassic and Permian red beds, P IP=Permian-Pennsylvanian red beds. Even-crested ridges are probably not much below the level of a Tertiary erosion surface. Flat terraces in the Roaring Fork valley are glacial outwash gravels. ➤

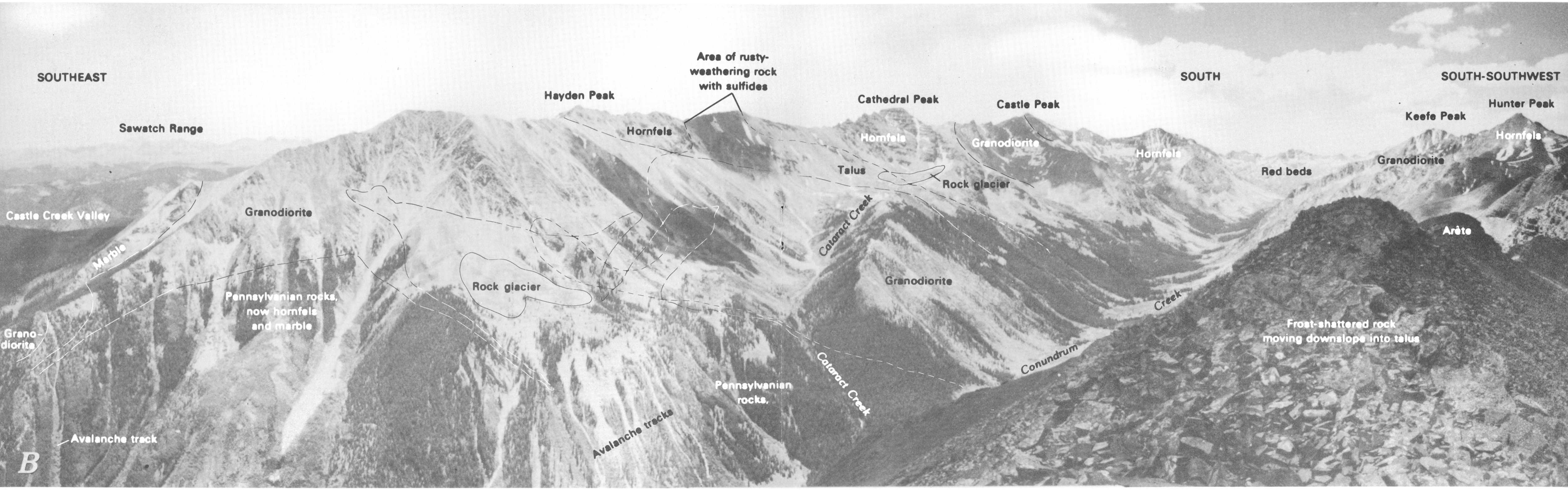


Plate 1B

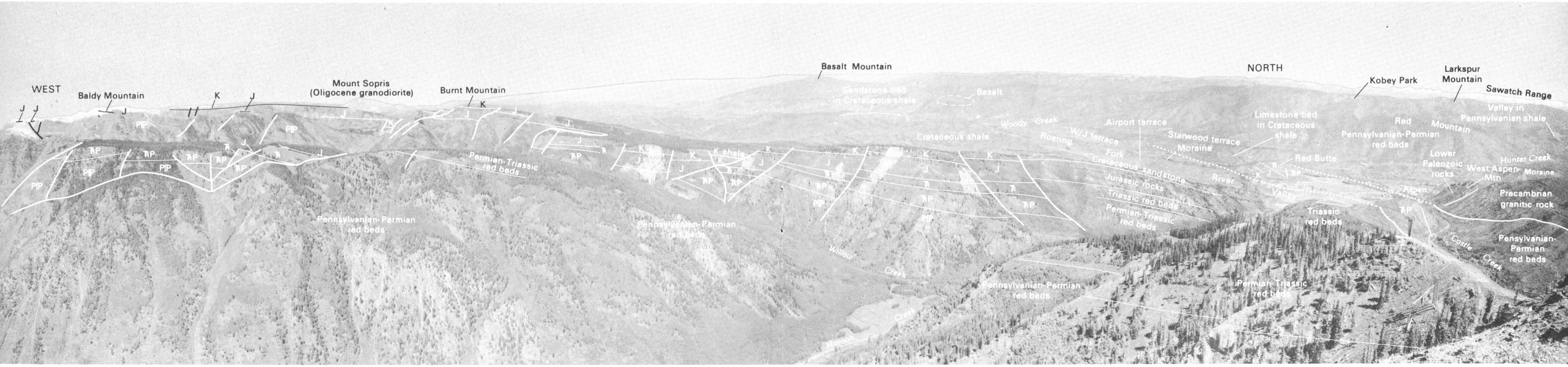


Plate 1C

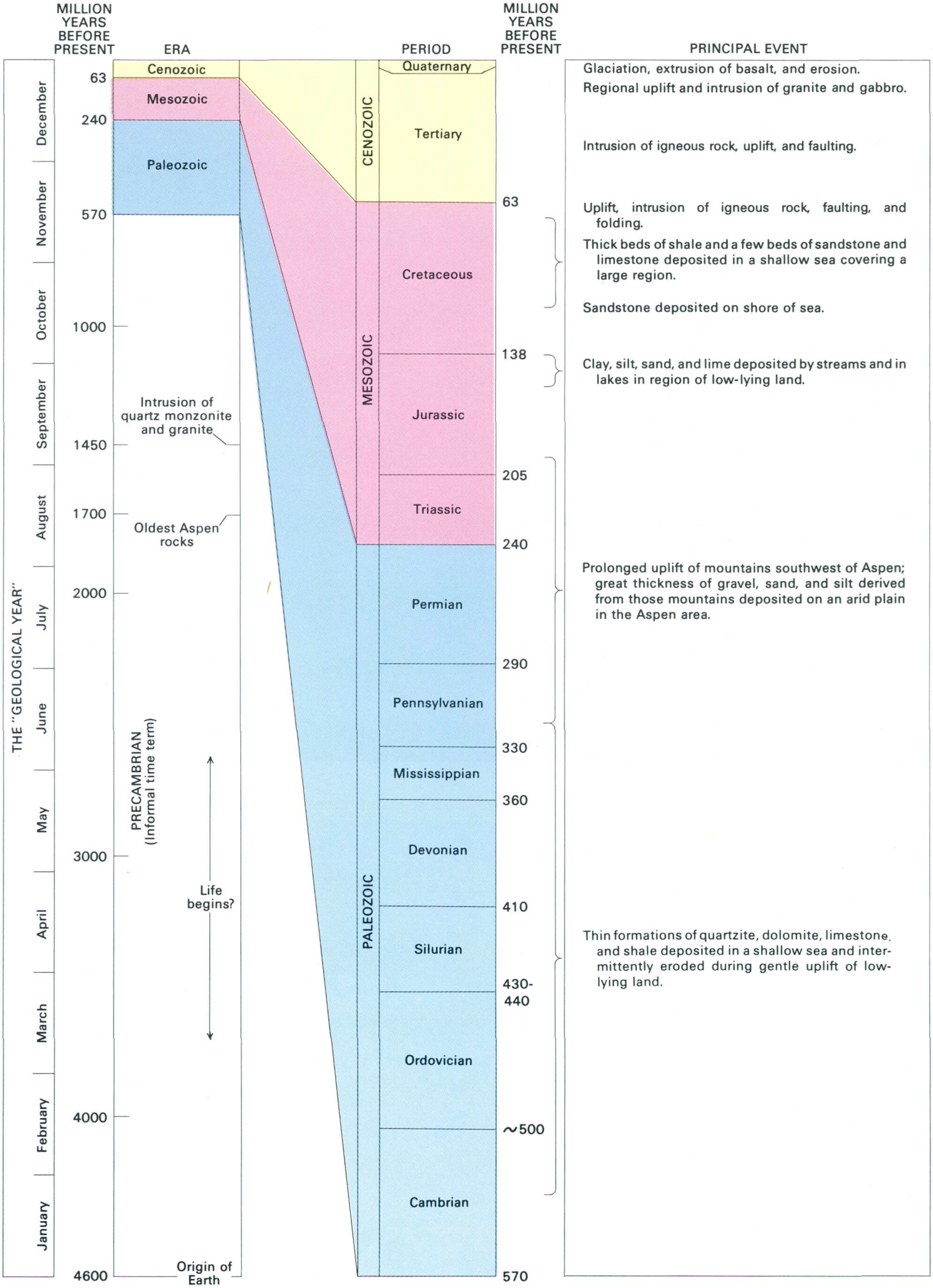
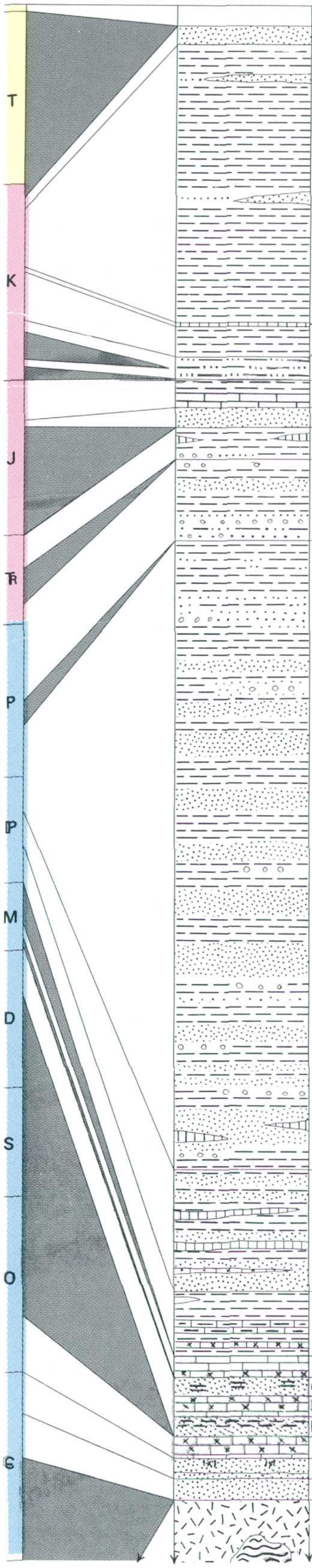
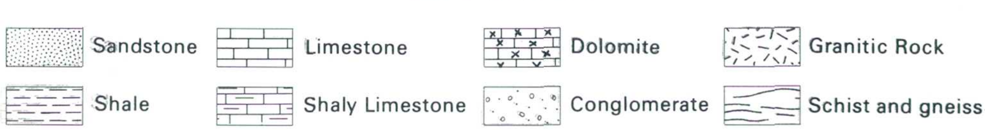


Figure 14. The geologic time scale (left) and stratigraphic column of formations in the Aspen region (right). Geologic periods are drawn in proportion to the estimated time spans they covered; formations are drawn in proportion to their average reported thicknesses in the Aspen region (except for those averaging less than 300 feet). Diagonal lines in the Correlation column relate the rock units to their presumed periods of geologic time. Shaded areas represent unconformities ("missing chapters") in the stratigraphic record.



ROCK UNITS	THICKNESS (FEET)	DESCRIPTION	PAGE REF
Quaternary deposits	0-500	Basalt; glacial and stream deposits.	15-20, 47
Mesaverde (?) Formation	125	Grayish-yellow-weathering sandstone.	39
Mancos Shale; Fort Hayes Limestone Member	5200	Dark-gray shale and silty and sandy shale containing zones of concretions. Contains lenses and beds of yellowish-gray-weathering sandstone. Fossils of marine mollusks abundant, especially in upper half. Light-gray limestone bed (Fort Hayes Limestone Member), about 40 feet thick, occurs about 400 feet above base and locally contains large fossil clams.	38-39
Dakota Sandstone and Burro Canyon Formation	145-425	Gray and white sandstone; some beds of shale, siltstone, and conglomerate.	38
Morrison Formation	300-530	Grayish-red and greenish-gray siltstone and claystone, calcareous siltstone, and sandstone. Dark-gray limestone and light-gray sandstone near base.	38
Entrada Sandstone	0-150	Yellowish- to pinkish-gray sandstone.	37
Chinle Formation	0-900	Reddish-brown to red siltstone and pinkish-gray limestone and limestone-pebble conglomerate. Lenses of quartz pebble conglomerate at base.	37
State Bridge Formation	0-2500	Moderate-reddish-brown to reddish-orange siltstone, sandstone, and conglomerate.	35-37
Maroon Formation	1200-15,000; 10,000 in Maroon Bells area	Grayish-red to moderate-red sandstone, siltstone, mudstone, and conglomerate. Beds of gray limestone in lower part. Some gray sandstone and conglomerate beds. Local bed of white anhydrite near base. Conglomerates contain pebbles and cobbles of Precambrian and Paleozoic rock eroded from the Uncompahgre highland to the southwest. Plant fragments and impressions locally occur.	34-35
Gothic Formation (of Langenheim, 1952)	1000-3000	Yellowish-brown-weathering gray sandstone, siltstone, and limestone. Some brown and red beds near top. Local beds of white anhydrite. Abundant marine fossils in some limestones south of Elk Mountains.	34
Belden Formation	500-1500	Dark-gray limestone, dolomite, and shale, carbonaceous in many places. Rare beds of white anhydrite. Limestone beds locally contain marine fossils.	33
Leadville Limestone	100-200	Upper part gray limestone; lower part dolomite.	33
Gilman Sandstone (Chaffee Group)	4-15	Gray sandstone, dolomite, sedimentary breccia.	32
Dyer Dolomite (Chaffee Group)	50-100	Gray; contains a few beds of limestone.	32
Parting Formation (Chaffee Group)	50-100	Quartzite, shale, siltstone, and dolomite.	32
Manitou Dolomite	150-250	Gray; white chert stringers and nodules.	32
Peerless Formation	100-150	Predominantly grayish-orange dolomitic sandstone and dolomite, and red to greenish-gray shale.	32
Sawatch Quartzite	150-250	White to pale gray.	32
Precambrian rock	Thickness unknown	Quartz monozonite, granite, and mica schist and gneiss.	29

EXPLANATION



Layers of sedimentary rock near Aspen have been correlated with those throughout the Rocky Mountain region; many layers of rock near Aspen have the same general color, texture, and composition as rocks of the same age hundreds of miles away. If rock strata of the same age within a limited geographical area display many similarities, it is usually assumed that they were once part of one continuous bed of sediment. A *formation* is a rock layer, or a group of such layers, that has distinctive characteristics and can be traced for some distance. All the sedimentary rocks of the Aspen area have been assigned to formations, and many of these bear the names of the distant places where they were first described. Thus we have the Morrison Formation, the Mesaverde Formation, and the Dakota Sandstone, for instance.

A *relative age* has been determined for each of these formations, either from its own fossil content or from its relationship to fossil-bearing formations. Relative ages cannot be given in years. Rather, they are expressed in terms of the geologic time scale (fig. 14). This scale has been refined by many decades of scientific dispute and discussion. It divides geologic time into *eras* and *periods*, generally on the basis of the kinds of fossils found in rocks of each age. Precambrian time, at the bottom of the scale, represents nearly nine-tenths of Earth history; few fossils of any sort are found in Precambrian rocks, for the plants and animals of that age were small and had soft bodies. Paleozoic rocks contain abundant fossils of shellfish and creatures with simple skeletons. The Mesozoic Era, roughly speaking, is the Age of Reptiles, when dinosaurs and their kin ruled the planet. The Cenozoic Era, which continues to the present, is the Age of Mammals. Only in the last 2 million years of this era—in the Quaternary period—has modern man appeared, and he has come to be the dominant mammal only in the last 10,000 years or so, a time known as the Holocene Epoch.

Inasmuch as this time scale was based on the fossil content of sedimentary rocks, their relative ages can usually be determined without difficulty. But the age assignment of igneous rocks is a problem, for they rarely contain fossils. The lava flows and layers of ash that pour forth from volcanoes are deposited at the surface just like layers of sediment. Hence, they will be in their correct stratigraphic position, and their relative ages can be determined from the ages of overlying and underlying sedimentary strata. However, most of the igneous rock in the Aspen area is not volcanic, because much rising magma cools and solidifies before it ever reaches the surface.

Great masses of molten rock invade the sedimentary layers from underneath and often destroy parts of the lower layers. Fiery "fingers" push upward from the main mass along weaknesses in the rock. Some of these fingers erupt at the surface, but others are trapped and form pools within the sedimentary strata. In some cases, the trapped magma may force its way between two preexisting sedimentary layers and spread out thinly to form its own layer. Such igneous layers defy Steno's rule that the youngest layer is on top.

After thousands (or perhaps millions) of years the whole molten structure cools and solidifies. The resulting igneous rocks may eventually be exposed by erosion, as they have been at Aspen. These rocks cannot be dated on the basis of their position, and they cannot be dated from fossils, for they contain none. Their age can be inferred, though, because the intrusion of hot magma usually leaves its mark on all strata present, even though the intrusion itself may not reach the higher layers. Such intrusions can cause the ground to swell; the surface layers may slant and fracture; and superheated ground water may circulate through the rocks, leaving characteristic deposits. Sedimentary beds laid down after the slanting occurs will appear misaligned and will not have the same fractures and hot-water deposits. If ages have been determined for these undisturbed beds and for the underlying fractured layers, then the relative age of the igneous intrusion is known.

All these relative ages are useful in reconstructing the chain of events that constitutes the geologic story of the Aspen region, but they cannot tell us whether that story spans a few thousand years or a few billion. Many ingenious schemes have been devised for dating geological events, but the most reliable method now available involves the measurement of radioactive elements.

Marie and Pierre Curie discovered in France in 1898 that uranium gradually changes to other elements.[2] A few years later, English scientists Lord Rutherford and Frederick Soddy determined that this transformation proceeds at a regular, predictable rate. These discoveries paved the way for *radiometric dating* of rocks. It is now known that several elements other than uranium are subject to this process called *radioactive decay*. All rocks contain minute amounts of radioactive material, most of which is concentrated in certain minerals, and sensitive instruments available since World War II can tell how much of this material has decayed. Because precise rates of decay have now been determined for all radioactive elements, it is purely a matter of mathematics to determine how many years have elapsed since the mineral containing the radioactive material crystallized.

Radiometric age determination is not really as simple as this description implies. Measurements that are less than meticulous can result in errors of hundreds of millions of years. Furthermore, some products of radioactive decay can escape from the rocks if they are reheated or weathered.

[2]The Curies used pitchblende ore from Central City—not too far from Aspen—for some of their pioneer work!

This latter problem makes the choice of a rock for radiometric dating important; the minerals composing the rock must have crystallized when the rock formed and must not have been altered by subsequent heating or weathering. Consequently, sedimentary rocks, which are commonly composed of mineral grains derived from older rocks, generally cannot be radiometrically dated. Nevertheless, it is generally accepted that carefully conducted radiometric dating yields fairly reliable ages for igneous rocks. As explained above, these igneous rocks can be correlated with sedimentary strata in various ways. Thus these radiometric dates can be confidently related to the geologic time scale. The dates shown for each geologic period in figure 14 are the best available but are not precise. Some of the oldest dates may actually be in error by 10 or 20 million years, but this is a minor uncertainty, because geologic time spans hundreds of millions of years.

Radiometric dating near Aspen has shown that the geologic story of the area began about 1.8 *billion* years ago. The rock strata near Aspen have been extensively studied: their succession has been established, relative ages have been assigned, their relation to similar rocks throughout the Western United States has been determined, their radiometric dates have been obtained wherever feasible, and their present distribution has been mapped (fig. 15). In this manner, the events of this 1.8-billion-year history have been elucidated.

Ancient Rocks of the Earth's Crust

Some of the oldest rocks in Colorado are found about 12 miles southeast of Aspen, where Colorado 82 winds across the Sawatch Range. The thin, twisted and tortured layers of light-gray metamorphic rocks that form the core of these mountains began as loose sediments and lava flows at the bottom of a sea sometime between 1,800 million and 1,700 million years ago. Other rocks and sediments accumulated on top of them and, about 1,700 million years ago, the heat and pressure on them became so intense that their basic character changed. Most of the layers metamorphosed to *mica schist* or *gneiss*, but some became *amphibolite* and others recrystallized to coarse-grained granitic rock. At the same time, the flat-lying layers were deformed in a complex pattern, suggesting that they had the effective consistency of soft plastic.

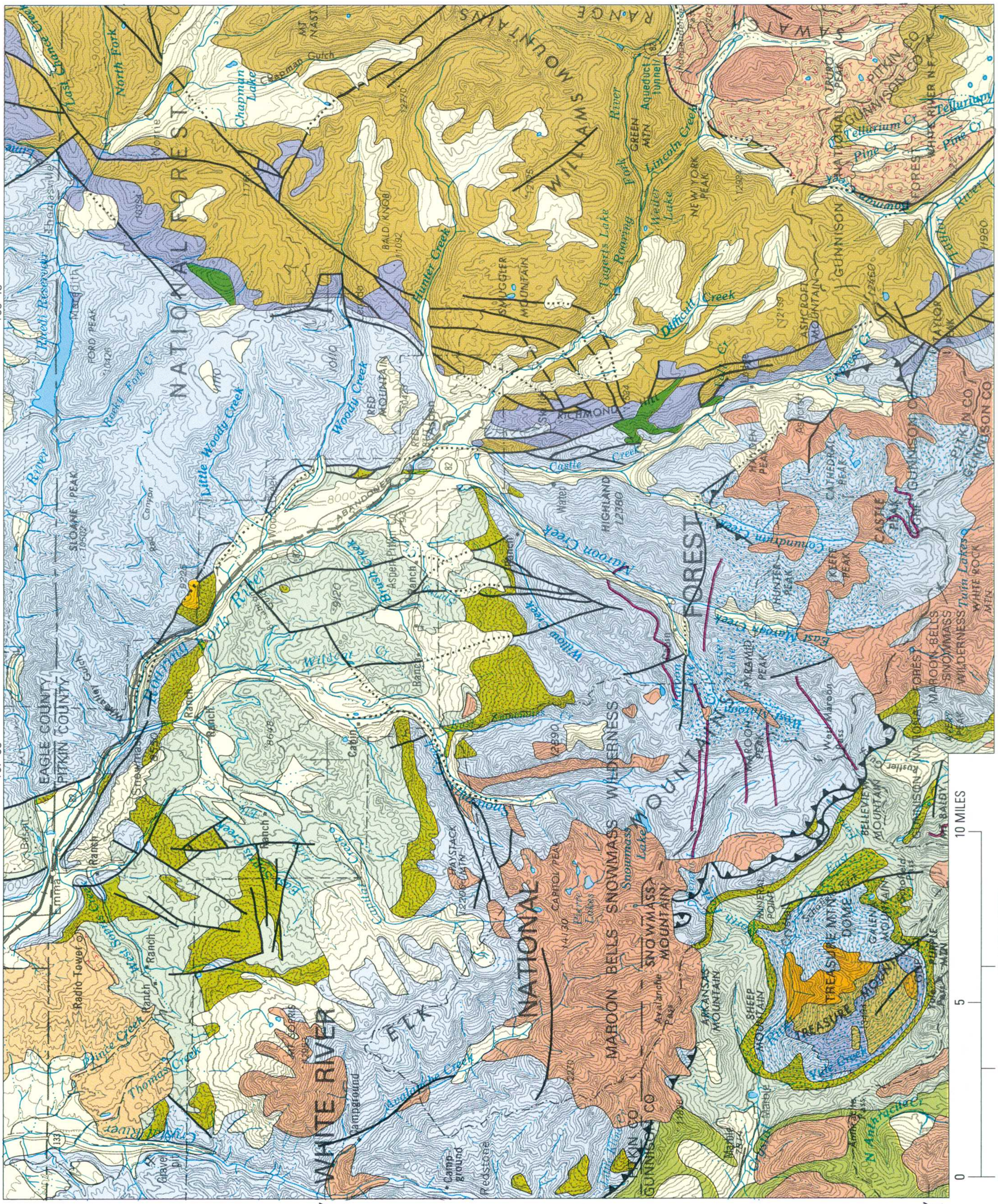
These most ancient rocks can now be seen in many places east of Aspen, but they are not nearly so common as are younger rocks (fig. 15). In the schist and gneiss, small, shiny flakes of mica that lie roughly parallel to the rock layers are cemented by grains of pale-gray feldspar and quartz. Thus the rocks are said to be *foliated*, for their whole internal structure is aligned in a series of more-or-less parallel planes, which in most rocks is parallel with their layering (fig. 16). The few layers of amphibolite contain much black hornblende, and therefore appear much darker than the schist and gneiss. Wherever the granitic rock occurs, as along the lower part of Lincoln Creek near Colorado 82, it is so tightly interlayered with mica gneiss that the resulting rock is called *migmatite* ("mixed rock").

The metamorphism of these rocks must have taken place at great depth, because the mica schist contains thin, white fibers of *sillimanite*. Laboratory experiments have shown that this fibrous mineral most likely crystallized under temperature and pressure conditions that probably would have existed 6 miles or more below the surface in this area.

Apparently, the schist, gneiss, and amphibolite were still deeply buried 1,450 million years ago, when hot magma invaded the rocks. This molten material cooled to become granite and *quartz monzonite* (which is very similar to granite). Igneous rocks now dominate the scenery between Aspen and Independence Pass. They are light gray, like the gneiss and schist, but where they have been exposed to weathering for many years, the outermost layers assume a pale-orangish-pink tone. Also, the granite and quartz monzonite occur in solid masses, not in thin layers.

Following the intrusion of igneous rocks 1,450 million years ago, great events must have taken place in the Aspen region, but their exact nature and sequence are not known, for there is a 900-million-year gap in the stratigraphic record—the next oldest rocks found anywhere in the area are 530 million years old. Such "missing chapters" of geologic history are referred to as *unconformities* (fig. 14). In this case, we have a whopping unconformity that spans one-fifth of the history of the Earth!

What we do know is this: 530 million years ago, sandy ocean sediments were deposited directly on top of ancient rocks that contained sillimanite, the layers of gneiss and schist that had once been buried 6 miles deep now were near the surface, and the tremendous thickness of rock that had overlain them was completely lost to erosion. The metamorphic rocks and the younger granite they contained had been bent, broken, and locally recrystallized along linear belts called *shear zones*. (These shear zones would later be important to Colorado, for they provided many favorable sites for the formation of ore deposits during the Tertiary Period; see p. 41). Clearly, the Aspen area had undergone an episode—or several episodes—of great uplift, erosion, and shearing stress during the "missing" 900 million years. But the shearing must have ended before the thin sedimentary rocks were deposited 530 million years ago, for they were not affected by it.


106°45'
107°00'
39°15'
39°00'
EAGLE COUNTY
PITKIN COUNTY
WHITE RIVER
NATIONAL
FOREST
ELK
MOUNTAINS
WILLIAMS
MAROON BELLS SNOWMASS WILDERNESS
SNOWMASS MOUNTAIN
TREASURE MTN DOME
GUNNISON CO
PITKIN CO
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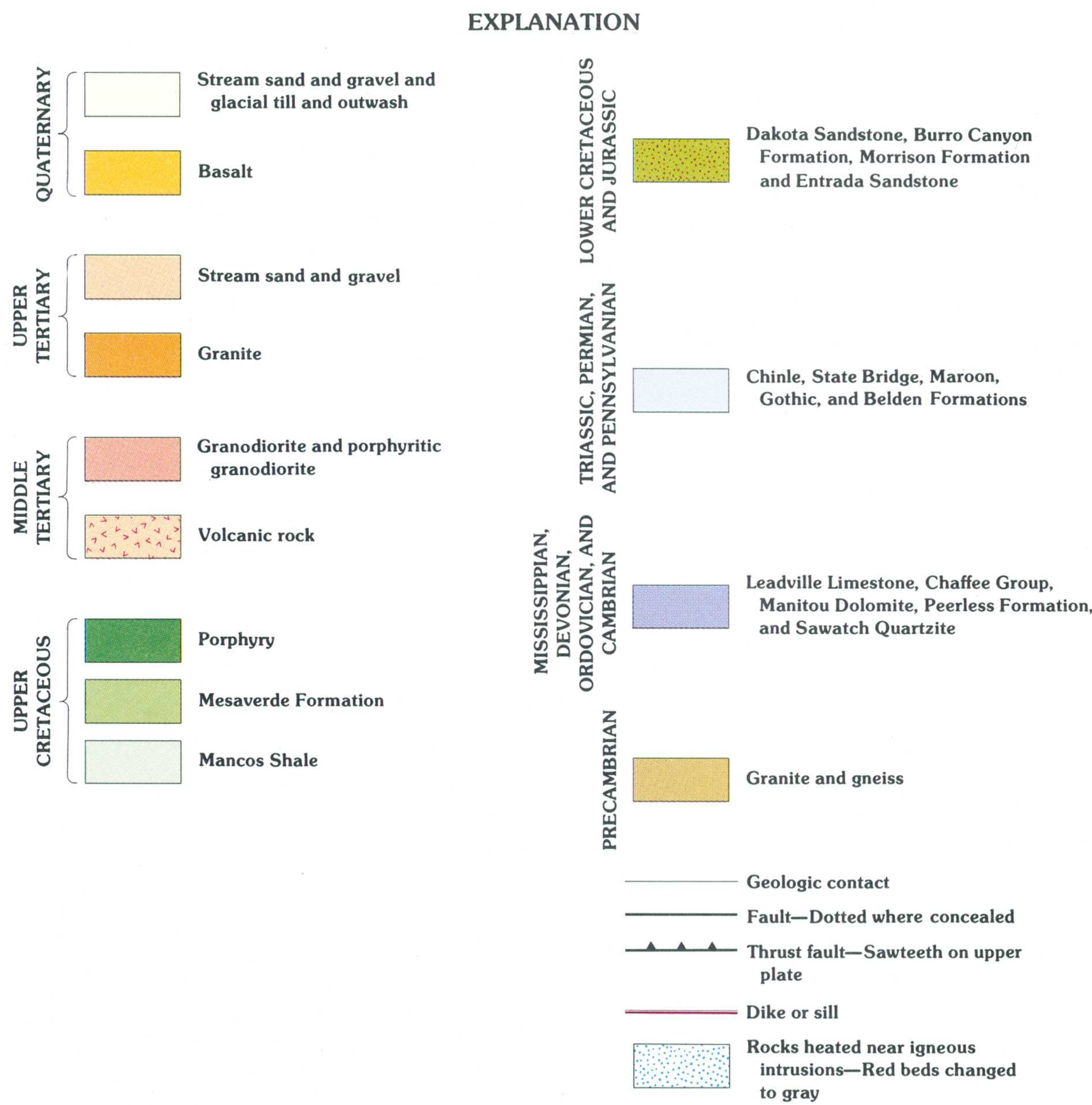


Figure 15. Generalized geologic map of the Aspen region. Most of the folding and faulting shown here took place 65 to 70 million years ago when the Sawatch Range was uplifted. The large bodies of granodiorite forming the Snowmass and White Rock plutons were intruded 30 to 35 million years ago and caused some uplift, faulting, and metamorphism in the area of the present Elk Mountains. Map modified from compilations of the Leadville 1:250,000 quadrangle by Ogden Tweto, R.H., Moench, and J.C. Reed, Jr., and of the Montrose 1:250,000 quadrangle by Ogden Tweto, T.A. Steven, W.J. Hail, Jr., and R.H. Moench. These compilations were based in part on the more detailed geologic maps listed in the section, "Geology and Land-use Planning in Aspen."

The Early Paleozoic—Much Time and Thin Rocks

From Late Cambrian time (530 million years ago) until the end of the Mississippian Period (320 million years ago), the Aspen area was alternately submerged in a shallow sea or barely exposed above sea level. The sea that slowly encroached on the area in the Late Cambrian was alive with small, hard-bodied creatures; most of these were trilobites, but brachiopods and other primitive mollusks were also abundant. (Unfortunately, few fossils have been found in rocks of this age near Aspen.) Meanwhile, the nearby land was barren, for no life yet existed there; no vegetation checked the onslaught of rain and wind. The ancient crystalline rocks of the land surface were torn into tiny grains of quartz and clay minerals, which were washed away, or blown away, toward the encroaching sea.

The fine sand that settled on the beaches and near the shore of this Cambrian sea was nearly pure quartz; the smaller grains of clay were carried farther out to sea. As time passed and sediments accumulated, this quartz sand was compacted until the individual grains merged into a hard, white rock called *quartzite*. The bed of rock that resulted, now recognized as the oldest formation of sedimentary origin in the Aspen area, is called the Sawatch Quartzite.

Farther offshore in the Cambrian sea, calcium and magnesium carbonates precipitated from the warm, shallow water and formed *dolomite*, which mixed with sand and clay minerals from the land. As the land retreated farther from the Aspen area, the supply of sand dwindled, and the sediments on the ocean floor gradually changed from sand, to dolomitic sand, to sandy dolomite, to dolomite. This was not a steady progression (few geologic processes are truly steady); the proportions of sand and dolomite fluctuated greatly, but by Early Ordovician time (500 million years ago) the sediments were primarily dolomite. Above the Sawatch Quartzite in the Aspen area, geologists now recognize a transitional sequence of intermingled sandstone and dolomite called the Peerless Formation, which is overlain by the Manitou Dolomite (fig. 14).

No rocks in the Aspen area remain from the period between 480 million and 360 million years ago (Middle Ordovician to Middle Devonian). Evidence from other parts of the western United States suggests that sediments were deposited during the early part of that time span but were later removed by erosion after the land emerged from the sea.

In Late Devonian time the sea gradually returned. Once again, a bed of pure quartz sand was laid down and was soon buried by a complex, transitional sequence of dolomitic sand and sandy dolomite, interlayered with mud and silt (which formed shale and siltstone). For the first time, the bodies of primitive fish mingled with the sediments, and their fossil remains are now found near Aspen in the rocks of the Parting Formation. As before, the transitional sequence eventually gave way to sediments that were predominantly dolomite, now called the Dyer Dolomite. Then, sometime around 345 million years ago, the shallow sea briefly retreated, then returned to deposit another sandy dolomitic sequence called the Gilman Sandstone.

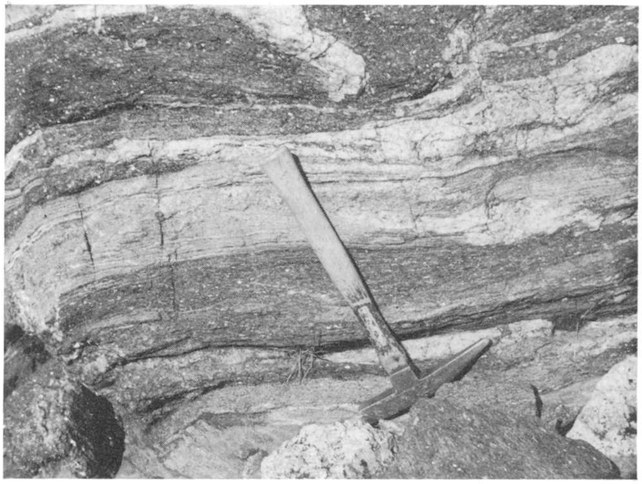


Figure 16. Well-foliated mica schist (dark gray) and gneiss (light gray), like that found in the Aspen area, with some lenses and stringers of pegmatite (white, coarser grained rock). Foliation is formed by aligned flakes of mica (both biotite and muscovite).

Because the Parting Formation, the Dyer Dolomite, and the Gilman Sandstone have many similar characteristics and form a continuous sequence (with only one small unconformity), they are known collectively as the Chaffee Group[3] (fig. 14).

The sea that covered the Aspen area 340 million years ago (Early Mississippian) was similar to all previous Paleozoic seas: shallow and warm. Like those seas, it deposited many thin layers of gray dolomite as calcium and magnesium carbonate precipitated from it. But subtle changes took place in these waters as time passed: the conditions of temperature, depth, and salinity became almost ideal for abundant marine life. The calcareous shells and skeletons of coral, mollusks, sea lilies, and many microscopic creatures rained down on the sea floor. The amount of calcium carbonate in the sediments greatly increased as the magnesium carbonate decreased, and the sediments soon changed from gray dolomite to blue-gray lime mud. The thick beds of limestone that formed from this mud were known simply as the "Blue limestone"

[3]Older publications sometimes combined the Parting and the Dyer into the "Chaffee Formation," and assigned the Gilman to the Leadville Limestone.

to early prospectors near Aspen, and they were explored thoroughly, for the prospectors recognized them as the same strata that contained rich silver and lead deposits at Leadville (See p. 7). Today this blue-gray limestone and the dolomite beds beneath it are called the Leadville Limestone. Much of the precious ore it contained is gone, but it still contains a wealth of fossil fragments from the Mississippian sea.

In Late Mississippian time (about 330 million years ago), the region again was elevated above the sea and erosion began on top of the newly formed limestone. The resulting unconformity, which is now found at the top of the Leadville Limestone, marks a turning point in Aspen's geologic story. All the sediments below this point were deposited in shallow seas and are very thin. They represent about 200 million years, yet their total thickness is less than 1,000 feet. Above the Leadville Limestone, the individual formations exceed this thickness, though some represent only a few million years (fig. 14). As we shall see, most of these thick formations also had a radically different depositional environment.

Although the lower Paleozoic formations are thin in the Aspen area and form little of the landscape, they are relatively conspicuous because they were later tilted up, and beds of resistant limestone, dolomite, and quartzite protrude from the hill slopes. They are exposed along the western edge of the Sawatch Range in a narrow, curving belt that extends from Taylor Peak to Aspen to Lenado. They form cliffs on East Aspen Mountain and West Aspen Mountain (locally called Shadow Mountain, fig. 17) and in Spar Gulch, and slabby outcrops line the east side of the Castle Creek valley just north of Ashcroft.

Mountain Uplifts and Thick Rocks— The Later Paleozoic and Early Mesozoic

In Pennsylvanian time (about 315 million years ago), a great change began in the surface of the Earth's crust in the region. This change laid the groundwork for today's scenery, for the red rocks that formed during this event compose the spectacular peaks of bedded rocks, such as Castle Peak, the Maroon Bells, and Pyramid Peak—unique attractions of the Southern Rocky Mountains.

Near Aspen, downwarping of the ground created a low area that was flooded by the sea. This area has been called the Eagle basin. Then the land gradually began to rise a few miles south of the present Elk Mountains and also northeast of Vail. The uplift eventually formed two mountain ranges, which trended northwest, unlike many of the present ranges in Colorado. These were the Ancestral Rockies. The range to the northeast was the Front Range highland, and that closer to Aspen, to the southwest, was the Uncompahgre highland (fig. 18). The ranges persisted, at least intermittently, for 150 million years, but they were highest and best defined for about 100

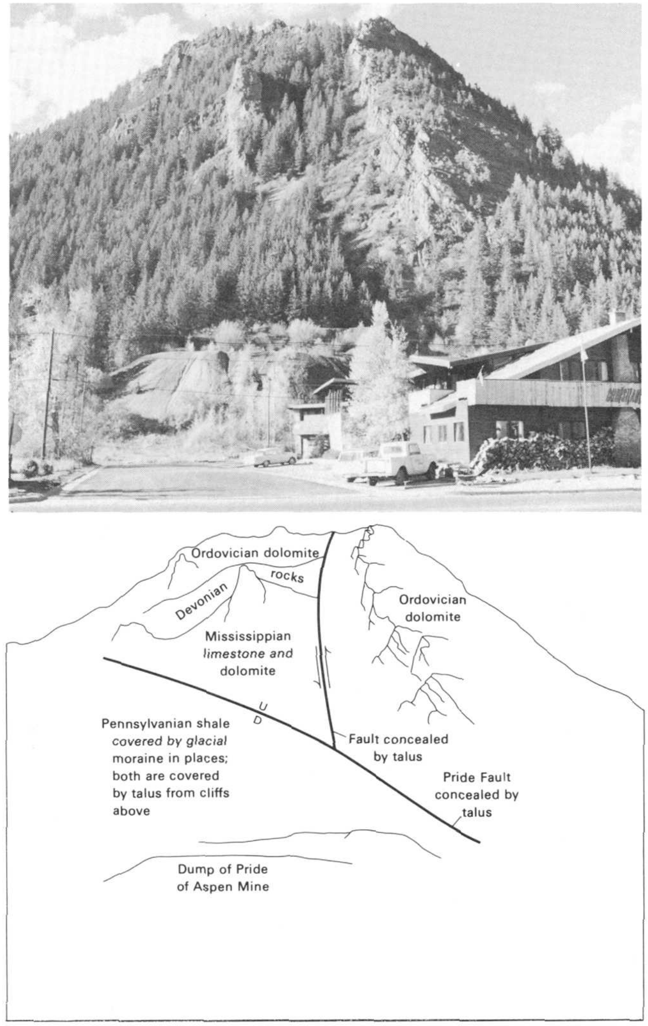


Figure 17. Faulted lower Paleozoic rocks on West Aspen Mountain. Sketch shows faults and rock formations of the photograph. From this angle it looks as if the older Ordovician and Devonian rocks are above the younger Mississippian rocks in the fault block in the upper left part of the view. That is because the beds dip toward the camera more steeply than the mountain slope does, and the beds beneath the Mississippian rocks are exposed higher up the mountain. The Pride fault served as a conduit for metal-bearing solutions that deposited silver ore in and near the fault. The Pride of Aspen mine had several workings in and along this fault. View looking south.

million years during Pennsylvanian and Permian time.

Before the major uplift of these mountains began, shale, limestone, and fine-grained sandstone beds of the Belden Formation (fig. 14) were deposited in the part of the Eagle basin near Aspen. Some of these beds contain fossil brachiopods (creatures that resemble clams but are not closely related), and other beds are rich in plant fragments. The brachiopods probably lived far from land in the shallow sea, but the plant fragments were deposited in coastal swamps. Apparently, the land near Aspen was low and flat in Early Pennsylvanian time, and the shoreline migrated freely.

Then, in Middle Pennsylvanian time, the Ancestral Rockies began to rise nearby, even though the Aspen area remained underwater. These mountains did not rise at a steady rate. At times when the Uncompahgre highland rose rapidly, steep, vigorous streams carried large quantities of coarse sand into the Eagle basin; when the uplift was slower, the streams carried fine silt; and when the uplift halted altogether, the sediments in the Eagle basin consisted primarily of lime mud that precipitated directly from the seawater. These sediments now form the sandstone, siltstone, and limestone of the Gothic Formation,[4] which overlies the Belden Formation.

As the mountains rose on each side of the Eagle basin, it was slowly cut off from the open sea, and the water near the center of the basin soon became too salty to support marine life. This high salinity probably explains why no fossils have been found in the Gothic Formation near Aspen. But near the edges of the basin, the inflow from mountain streams freshened the water and made it habitable. Consequently, fossils of many kinds of mollusks have been found in the Gothic Formation south of the Elk Mountains, in an area that lay near the shore of the Uncompahgre highland in Pennsylvanian time.

Farther from land, in the Aspen area, the influx of fresh water had less influence, and it could not always keep pace with evaporation. The mineral content of these waters rose as evaporation proceeded, and one of the first compounds to reach the saturation point and crystallize was calcium sulfate. This substance first solidifies as *gypsum*, but if heat and dry air remove all traces of moisture, it becomes *anhydrite*.

Some white beds of anhydrite and gypsum are found in the Gothic Formation near Aspen; but nearer the center of the Eagle basin, around Carbondale, Eagle, and Gypsum, similar beds are thousands of feet thick. Deposits of this sort—called *evaporites*—indicate a dry and probably warm climate. Many evaporite beds are presently forming in the dry basins of Nevada and Utah, where several large lakes have evaporated since the last glacial period.

These evaporites do not make trustworthy foundations, either for the structures of man or for the overlying rock layers, because anhydrite is a parched rock with a powerful thirst. When it comes into contact with water, the rock swells and converts back to gypsum. Then, if the gypsum dries out, the rock compacts again. But if a lot more water flows into the gypsum, it starts to dissolve and becomes semifluid, like toothpaste.

At Monument Gulch, 10 miles south of Aspen, a bed of evaporite lies just below the surface, and the overlying rock—a calcareous siltstone—has been broken and shattered by the heaving and shifting of the evaporite.

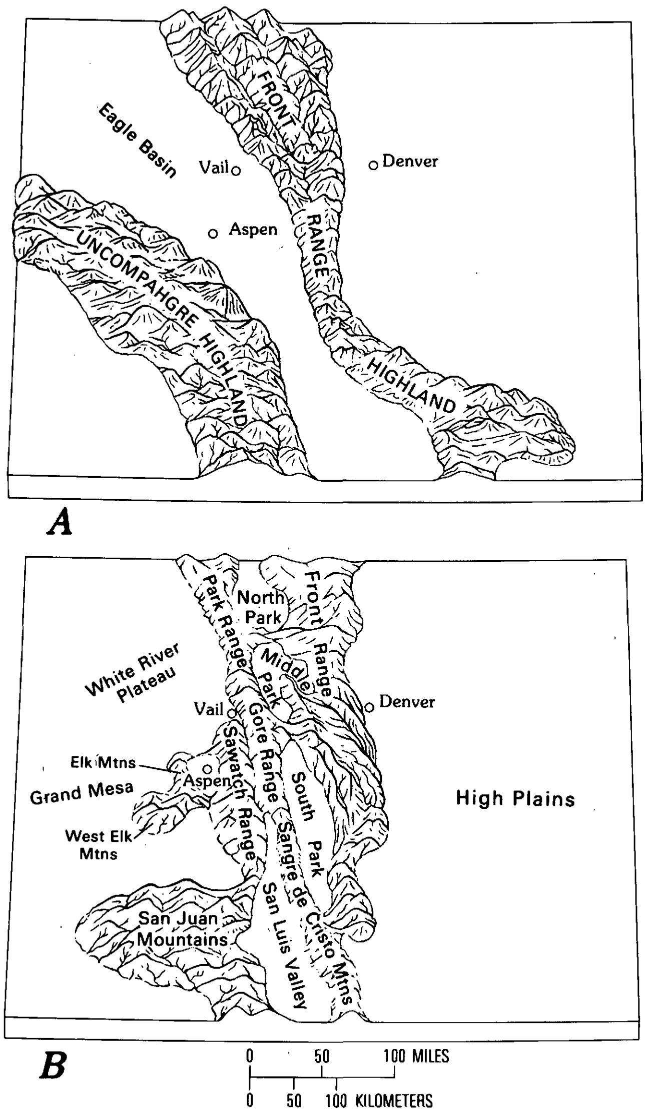


Figure 18. *A*, The Ancestral Rockies in Middle Pennsylvanian time (according to W. W. Mallory, U.S. Geological Survey). *B*, The modern Rocky Mountains within Colorado.

A rock consisting of such small, broken fragments is called a *breccia*. At Monument Gulch, erosion has carved the breccia into the towering monuments that give the place its name (fig. 19).

Most of the rocks in the Gothic Formation are various shades of gray and brown, but some of the higher layers assume a distinctly reddish hue. The point where red begins to predominate over the other colors marks the base of the Maroon Formation.

The increasing redness of the rock strata reflects the withdrawal of the salty water from this part of the Eagle basin about 300 million years ago. Near-desert conditions existed in the basin at that time. Hence, the lake diminished through evaporation. In addition, continued uplift of the mountains increased the flow of gravel,

[4] This is the name applied by R. L. Langenheim, Jr., in 1952. It has not been officially adopted by the U. S. Geological Survey.

sand, and silt into the Aspen area from the Uncompahgre highland, and alluvial fans many times larger than those now found near Aspen encroached into the basin.

The sediments that formed the Maroon Formation were not much different from those of the underlying Gothic Formation. The Maroon contains more large pebbles and cobbles, because the higher mountains of its time gave rise to more vigorous streams, but otherwise the constituents of the two formations are much the same. Yet their colors are strikingly different.

The red color of the Maroon Formation[5] is produced by the mineral *hematite*, which the chemist calls iron oxide, but which is more commonly known as a component of rust. Rust develops when iron is moistened and then exposed to the air. This hematite formed as the streams that deposited the Maroon shifted course, and left damp sediments containing iron-bearing minerals exposed. Then the rains, although infrequent, renewed this process each time they fell. The sediments in the Gothic Formation contain about as much iron as those in the Maroon, but the iron-bearing minerals in the Gothic Formation did not get changed to hematite because they were deposited at the bottom of a saline lake or sea and were not exposed to the air.

T. R. Walker of the University of Colorado has found that red sediments similar to those in the Maroon Formation are being formed today in northeastern Baja California, near the mouth of the Colorado River. Hence the climate of the Aspen area in Pennsylvanian time may have been much like that of Baja California today.

Throughout Late Pennsylvanian and Early Permian time (roughly 300 million to 250 million years ago), the rise of the Ancestral Rockies continued, and erosion kept pace. More than 10,000 feet of red sediments accumulated in the Eagle basin. Consequently, the Maroon Formation is now the thickest, most conspicuous formation in the Aspen region. It lines canyon walls along Maroon Creek and makes the scenery of the Elk Mountains spectacular. The Maroon accounts for most of the red-colored rocks around Aspen, including those on Red Mountain and (of course) the Maroon Bells (fig. 20). At some places south of Aspen, these red beds have been changed to a drab greenish gray by later heating caused by intrusions of magma. (See p. 43 and fig. 27).

Sometime during the Early Permian, the Uncompahgre uplift expanded in the direction of Aspen. The newly formed rocks along the southwestern edge of the Eagle basin were elevated and subjected to erosion. Elsewhere in the basin, the sandstones and siltstones of the Maroon Formation pressed down heavily on thick, light

Figure 19. Towering pillars of breccia project from the hillside at Monument Gulch, along the Castle Creek valley about 10 miles south of Aspen. The breccia consists of jagged fragments of siltstone, broken by the shifting and heaving of an evaporite bed that underlies this area. Some of the evaporite is exposed at places in the bottom of the gulch.

evaporite beds within the Gothic Formation. The semifluid evaporites shifted, flowed, and squeezed up through the heavier rocks in places, causing folding and tilting. The new sediments that now washed into the basin were much coarser than the fine sand and silt that had characterized the upper part of the Maroon Formation, for the source region was now much closer. These sediments formed coarse-grained sandstones and conglomerates of the State Bridge Formation, which now overlies the Maroon Formation in the Aspen area (fig. 14).

The State Bridge Formation is red like the Maroon, indicating that both were formed under the same general climatic conditions. Consequently, these formations are hard to tell apart at a glance. But a closer inspection reveals that many beds of the State Bridge display parallel symmetrical ripple marks, showing that some of it was deposited in standing water. The Eagle basin may have been briefly flooded by a shallow sea during deposition of the State Bridge Formation, but it seems likely that most of the ripple marks were formed in temporary lakes on a broad, flat, coastal plain.

The break between these two formations is easy to identify in the area north of Woody Creek, for there the beds of the Maroon Formation were tilted up sharply and planed off by erosion before the State Bridge sediments were deposited. The resulting misalignment of beds is an *angular unconformity*. Closer to Aspen, the beds above and below this break are parallel, and the contact must be located by careful inspection of the rocks. The

[5]It should be noted that the Maroon Formation actually was not named for the color of its rocks. Like most formations, it was named after a geographic feature: Maroon Creek. However, one suspects the name of this creek must have come from the distinctive color of the rocks that line its banks.

change in grain size is one clue. Also, the conglomerate beds within the State Bridge contain many bits and pieces of red siltstone that were torn from the upturned parts of the Maroon.

Near Aspen, the State Bridge is about 1,000 feet thick where it underlies the upper part of the Aspen Highlands ski area. It also forms the impressive red cliffs above the T Lazy 7 Ranch at the junction of Maroon and Willow Creeks. It becomes much thicker to the north and reaches a maximum of about 5,000 feet on Hardscrabble Mountain just south of Eagle.

The State Bridge has been correlated with the widespread Moenkopi Formation of Utah and Arizona, which formed from similar sediments that washed off the northwest and southwest flanks of the Uncompahgre uplift.

A third red formation, the Chinle Formation of Late Triassic age (200 million years old), lies above the State Bridge. Where the Chinle is exposed on the west side of Maroon Creek opposite the Aspen Highlands ski area, it rests on the State Bridge Formation with a slight angular unconformity (fig. 21). There, a distinctive orangish-brown sandstone bed at the top of the State Bridge tapers out and disappears (is *truncated*) beneath the Chinle. Evidently, this part of the Eagle basin was uplifted, tilted slightly, and eroded before the Chinle was deposited.

The Chinle Formation could easily be confused with either of the two underlying red-bed formations. But the Chinle consists mostly of fine siltstone and limestone; it has few of the coarse-grained sandstone and conglomerate beds that are so common in lower strata. The Chinle's sediments are like those deposited in shallow lakes and flood plains alongside slow-moving streams, at considerable distance from their source areas. Therefore, they did not come from any nearby part of the Uncompahgre highland; they may have come from a more distant part of that uplift, but it seems more likely that they had a completely different source area farther east or southeast.

In other parts of the Chinle Formation in Utah and Arizona, the sediments apparently did come from the direction of the Uncompahgre highland. Hence, parts of this upland area were still present in Late Triassic time, but as the part near Aspen was not a source for the sediments now found there, it may have been low ground at the time. If so, it must have risen again shortly after the Chinle was deposited, for no fragments of this formation are now found on the south side of the Elk Mountains. Furthermore, on the north side of these mountains, the rock layers of the Chinle Formation locally broke and slipped past each other before any of the overlying rocks were deposited. These breaks in the rock, called *faults*, were probably caused by the renewed uplift of the nearby highland about 170 million years ago.

Figure 20 (facing page). North Maroon Peak from the north. Gray talus and ledges in foreground are rock of the Maroon Formation that has been metamorphosed to hornfels. (See p. 43).

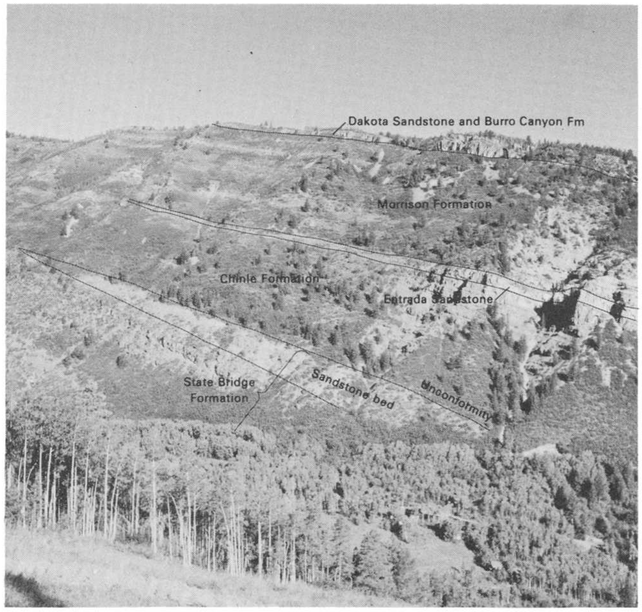


Figure 21. Mesozoic and Permian rocks on west side of the Maroon Creek valley viewed from the lower part of the Aspen Highlands ski area. An orangish-brown bed of sandstone in the State Bridge Formation tapers out and disappears where it was eroded before deposition of the Chinle Formation.

Uniform Environments Throughout a Broad Region—The Later Mesozoic

During the latter part of the Mesozoic (150 to 70 million years ago) the rocks deposited in the Aspen area (fig. 14) were like those deposited across a vast area of the western interior of the United States. No longer did sediment come from the Uncompahgre highland, for it had finally been leveled by erosion, and the Eagle basin had been filled. The sediments of late Mesozoic age covered them both. Sources of the sediments that composed the late Mesozoic rocks were to the south and west of Colorado.

The Aspen area lay on a low coastal plain at the beginning of Late Jurassic time (about 150 million years ago). A shallow sea covered most of Wyoming and Utah. Millions of years of erosion had removed parts of the Chinle Formation, exposing the underlying State Bridge and Maroon Formations. The low hills to the south of the area—the last remnant of the Uncompahgre highland—were made of Precambrian gneiss, schist, and granite.

Medium to coarse sand was blown into the area and deposited in a thin, discontinuous layer, mainly in low areas and sheltered spots. Today these sands form the yellowish-gray Entrada Sandstone, which stands in marked contrast to the thousands of feet of red rock beneath it near Aspen. Farther south, in the area of the old Uncompahgre highland where no red beds are found, this sandstone rests directly on Precambrian rock.

Several millions of years later, but still in Late Jurassic time, sluggish rivers from the south and west flowed through the Aspen area, bringing silt and clay from hundreds of miles away. They traversed a broad plain that extended from central Arizona and New Mexico into Canada. As the streams shifted course, lakes formed here and there, and thin beds of siltstone, sandstone, limestone, and clay were interspersed in a complex fashion. Some of these beds are dull green; others are reddish, yellowish, or just plain gray. All together, they compose the Morrison Formation.

The Morrison may be the most famous geological formation in the world, because it is so widely distributed in the West, because its varicolored rocks are so striking, and particularly because it contains dinosaur bones. Hundreds of these bones have been excavated from the Morrison at Dinosaur National Monument in northwestern Colorado and eastern Utah, and the largest complete skeleton ever found also came from this formation near the town of Morrison, Colo., for which the formation was named. But the only fossils yet found in these rocks near Aspen are small, roundish fruiting bodies of fresh-water algae called charophytes, which occur in the limestone beds. Elsewhere the Morrison contains other exciting things: it is the principal host rock for rich uranium deposits in the Four Corners region of Colorado, Utah, New Mexico, and Arizona.

Where the Morrison Formation comes to the surface in the Aspen area, it is usually covered by grass and soil, but its many-colored rocks can be seen across the valley of Maroon Creek from the Aspen Highlands ski area and along the sides of several gullies north of Willow Creek.

Near the beginning of the Cretaceous Period (about 135 million years ago) the land near Aspen evidently sank somewhat and the mountains that lay to the west rose higher, for the streams that flowed from that direction began depositing more coarse sand and pebbles. Also, the shoreline of a sea was approaching from the north. The white or pale-gray sandstones and conglomerates that formed at that time now compose the Burro Canyon Formation. As the sea encroached farther, its crashing waves formed sandy beaches near Aspen. In time, these beaches were overrun by the sea, and sea-bottom sands (undisturbed by wave action) were deposited over the beach sands. The Dakota Sandstone was formed from these beach and nearshore deposits. The beds of this formation are mostly white, light brown, or yellowish gray.

The sandstone beds of these two formations are slow to erode; hence they form prominent cliffs and ledges along the north side of the Willow Creek valley, on lower Maroon Creek, and on Eagle Mountain just west of the Snowmass ski area.

Figure 22. Mancos Shale containing prominent bed of sandstone on hill north of Brush Creek. View looking northeast. Fossils are relatively abundant in concretions in these Cretaceous shales. This steep south-facing slope at low altitude receives less precipitation than adjacent higher hills and mountains and is subject to more evaporation than slopes of other orientations. Consequently, the climate on this slope is too arid to allow forest growth.

By Late Cretaceous time (about 95 million years ago), the shoreline had migrated westward far enough that the coarse sand particles no longer reached the Aspen area. Instead, fine particles of mud and clay settled on this part of the ocean bottom and formed the Mancos Shale. In places, the thick beds of gray shale within the Mancos grade into limy shale and shaly limestone or into sandstone deposited in offshore bars (fig. 22). These strata accumulated more than a mile thick in the area. The conditions near Aspen were not unique at that time, for similar shale and limestone of the same age are found in a wide belt that extends from northern Canada to the Gulf of Mexico.

The Mancos Shale contains many marine fossils in its upper part. The fossils are best preserved in ellipsoid-shaped masses of hard rock called *concretions*, which are embedded in the relatively soft shale. The fossils are generally found where frost action has shattered one of the concretions. Where one fossil is discovered, careful search will usually reveal a number of others. The brush-covered hills 6-10 miles northwest of Aspen, near Besancon Gulch, Wildcat Creek, and lower Brush Creek, are prime hunting grounds for these fossils.

The Cretaceous sea teemed with many species of now-extinct marine mollusks: the ammonites (fig. 23). Their closest living relatives are the pearly nautilus and the squid. Each species of ammonite lived a relatively short span of geologic time (about 500,000 years; see time scale, fig. 14) and swam widely in the shallow seas

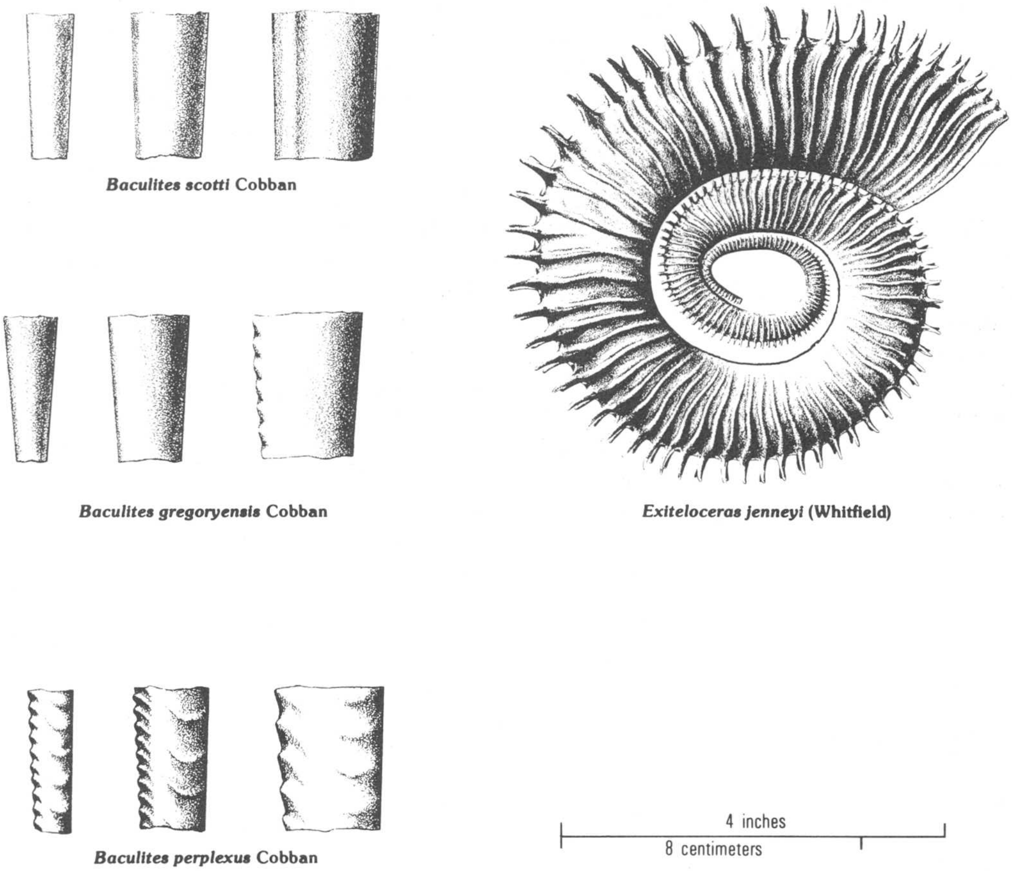


Figure 23. Some ammonites commonly found in the Cretaceous shales of the Aspen area. The drawings of *Baculites* are of fragments, the form in which most of the fossils are found. The oldest ammonite shown, *Baculites perplexus*, lived 74-76 million years ago; the youngest, *Exiteloceras jenneyi*, lived about 72 million years ago. Near Aspen, *Baculites perplexus* occurs through about 1,800 feet of rock in the middle part of the Mancos Shale, whereas the other fossils shown occur in much thinner sections of rock above the zone of *Baculites perplexus*. Drawings by Charles C. Capraro, Robert A. Reilly, and John R. Stacy.

then covering the middle of North America. Consequently, these ammonites make excellent *guide fossils* for use in correlating Cretaceous rocks throughout this part of the continent.

Furthermore, a series of Late Cretaceous volcanic eruptions hundreds of miles to the west conveniently spread several thin layers of ash, which can be dated radiometrically, among the sediments on the sea bottom. Thus we can fix the dates of the ammonite species that left their shells within these ash layers and can use these dates to reconstruct a detailed geologic history of the Late Cretaceous seas. Such a reconstruction would not be possible for the alluvial fans, plains, and lakes of the Permian or Late Pennsylvanian, because their red beds are almost devoid of fossils.

One of the highest ammonite zones in the Mancos Shale of the Aspen area has been radiometrically dated as about 72 million years old (fig. 23). Studies of rocks overlying this zone suggest that the Aspen area was under the Cretaceous sea until at least 71.5 million years ago and perhaps even later. Then, after 30 million years or so of relatively uniform conditions throughout the region, great changes began. Along the western shore of the sea, in Utah and Idaho, the land was rising, driving the sea to the east. Muddy sea bottoms were covered by encroaching beaches and swamps. The shoreline deposits formed at this time are interbedded with the muddy sea-bottom deposits in a way that shows how the position of the shore moved back and forth as it gradually migrated eastward over a period of several million years. These deposits are named the Mesaverde Formation, after the area in southwestern Colorado where Indians long ago built dwellings beneath overhanging ledges of sandstone in this formation.

Because of subsequent erosion, not much of the Mesaverde Formation remains near Aspen. West of the Crystal River in Pitkin County, miners today dig coal from the old swamp deposits of the Mesaverde. West of the Woody Creek post office, downvalley from Aspen, a hill is capped by sandstone that may represent the bottom of the Mesaverde Formation. This remnant of Mesaverde is the youngest marine bed found anywhere in the Aspen area, for the sea has not returned to central Colorado since its departure some 70 million years ago.

The end of the Cretaceous Period also closely coincided with several important ecological changes. The most striking of these is the sudden disappearance of the dinosaurs, after 150 million years of dominance. Just as puzzling, though, is the nearly simultaneous extinction of the ammonites, whose many species dominated the sea longer than the dinosaurs ruled the land. Over the years, innumerable theories have been advanced to account for these extinctions. Many recent publications have presented evidence that a large meteorite struck the Earth at this time, creating a cloud of dust and ash that blocked sunlight and disrupted the global ecosystem. This theory is intriguing and has gained wide support, but remains unproven.

The Birth of the Modern Rocky Mountains

The forces that wear mountains down are well understood, for they can be observed in action every day, and their progress can be measured from year to year. But the forces that raise mountains from featureless plains and seabottoms are still somewhat of a mystery, for they originate many miles below the surface and may be somehow related to other poorly understood geological events that occur thousands of miles away.

In Late Cretaceous time (70 million years ago), these forces were once again at work in the Aspen area, as they had been at least twice before. We now believe that this episode of upheaval and renewal, called the *Laramide orogeny*, was due directly or indirectly to the fact that the North American Continent was speeding westward at the astounding pace of 2 inches per year, overriding the rigid plate that forms the floor of the Pacific Ocean.

The orogeny established new mountain ranges along a broad path that extended from Alaska to Guatemala. Most of these ranges remain today, although they have been greatly changed by more than 60 million years of erosion, renewed uplift, and volcanism; they make up our modern Rocky Mountain system.

The orogeny began in the Aspen area about 72 million years ago, while the Cretaceous sea still covered the area. (See fig. 1F.) Four miles beneath the ocean floor lay the dark-gray beds of limestone, dolomite, and shale that had formed some 240 million years earlier, just before the rise of the Ancestral Rockies. These beds of the Belden Formation (see p. 33) and all underlying strata were intruded and pushed apart by hot magma that had risen from great depth. Shortly thereafter, the sea floor began its rise.

When the inland sea drained away from the Aspen area, the newly emerged land surface had a slight upwarp, which crested several miles to the east. Thus was born the Sawatch uplift, the direct predecessor of the modern Sawatch Range. As the uplift rose, its thin covering of Mesaverde sediments stretched, cracked, and began to wash away. As the uplift continued, the thick Mancos Shale was exposed and erosional forces intensified.

Erosion cut most deeply into the rocks along the crest of the rise. Lower on the sides, more than 20,000 feet of sedimentary strata were still intact. The tension within these beds increased sharply as the tilt of the sides steepened. Something had to give, and finally something did! Along the western side of the Sawatch uplift, a weakness developed within the Belden Formation and adjacent strata, and the overlying beds began to slide downhill.

Within an instant of geological time (perhaps less than a million years), a plate of rock about 4 miles thick and 30 miles wide slid several miles to the southwest. (See fig. 1G.) Most of the upper Paleozoic and Mesozoic rocks now exposed between Aspen and the crest of the Elk Mountains were part of this moving mass, which is called a *thrust sheet*. The sheet slid along a surface of broken rock known as a *thrust fault*.

Along the leading edge of the thrust sheet, rocks of Pennsylvanian age rode up over Cretaceous strata. All the intervening layers were caught up by the toe of the gravity-sliding thrust sheet and were literally folded back upon themselves. As a result, along the front edge of the thrust sheet now is a sequence of rocks in proper order that is overlain by an identical, upside- down sequence in reverse order, which is in turn overlain by much older, right-side-up rocks in proper order.

One of the earliest geological explorers of the Aspen region, F. V. Hayden, was fascinated by the puzzling display of warped, misaligned rock layers. In 1874, he wrote, "On the west side, in the Elk Mountains, the confusion is still greater, producing not only the most remarkable faults in all the western country, but literally overturning thousands of feet of strata."

The thrust fault and the overturned fold can be seen only by hikers in the high country. They are well exposed on the south side of the Elk Mountains at the head of the East Fork of the Crystal River, northeast of Schofield Park (fig. 15).

The gravity sliding of the thrust sheet must have happened before 67 million years ago, for that is the age of a mass of pale-gray igneous rock that apparently intruded along faults that cut the sheet after the sliding stopped. That rock, called *aplite*, represents just one of four types of igneous rock now found near Aspen that date from the rise of the Sawatch uplift. Three of the four types are white or pale gray; the fourth is greenish or bluish gray. They were formed by molten magma related to that which intruded the Belden Formation at the start of the Sawatch uplift. They are found mostly in that formation or older strata, in layers (called *sills*) 150 to more than 300 feet thick. Some of the lighter colored rock is in clear view along the east side of the Castle Creek valley, just north of Fall Creek (about 10 miles south of Aspen). The greenish- or bluish-gray rock is harder to see, for it readily crumbles into soil wherever it is exposed to weathering, but it does crop out on the sharp turn on the road south and slightly west of the Midnight Mine tunnel.

The igneous sills now exposed in the area are probably connected to larger bodies of similar rocks at depth. These rocks served as great reservoirs of geothermal heat during the Laramide orogeny. Great quantities of ground water were able to reach the deeply buried rocks before they cooled and to absorb some of their heat. This water was tightly confined by the weight of the overlying strata, and so it could attain temperatures hundreds of degrees hotter than its normal boiling point at the surface. The effect was much like that of a giant, subterranean pressure cooker.

The superheated water had unusual capabilities. It was able to dissolve tiny bits of silver, lead, and zinc that were widely dispersed in the rock, as well as many less valuable substances. Then, as the resulting weak but multifarious solution moved away from the magma bodies and began to cool, it traversed layers of rock whose chemical characteristics caused the precious metals to precipitate. Through thousands of years, small particles of metal in solution were swept up, carried about, and concentrated into distinct zones to make ore. Aspen acquired its great mineral wealth in this way.

The ore resulted from the interaction of two liquid agents: hot magma and ground water. These fluids required networks of passageways through the rocks to bring them into contact with each other. Aspen, as it happens, sits at the intersection of three such networks.

First, there is an ancient zone of weakness, a shear zone (see p. 29), in the Precambrian basement rocks beneath Aspen, which permitted the magma to rise into the upper part of the crust and, in small quantities, into the lower Paleozoic strata. This zone runs generally southwest to northeast across Colorado. It underlies the Colorado mineral belt, which contains most of the richest ore deposits in the state. In addition to Aspen, such famous mining towns as Silverton, Telluride, Leadville, Georgetown, and Central City lie within this belt above that ancient shear zone.

Secondly, the sedimentary rocks at Aspen have extremely permeable zones along unconformities, which are nearly parallel with their bedding. These zones are in or adjacent to the Leadville Limestone, whose carbonate rocks provide a chemically favorable environment for deposition of ore.

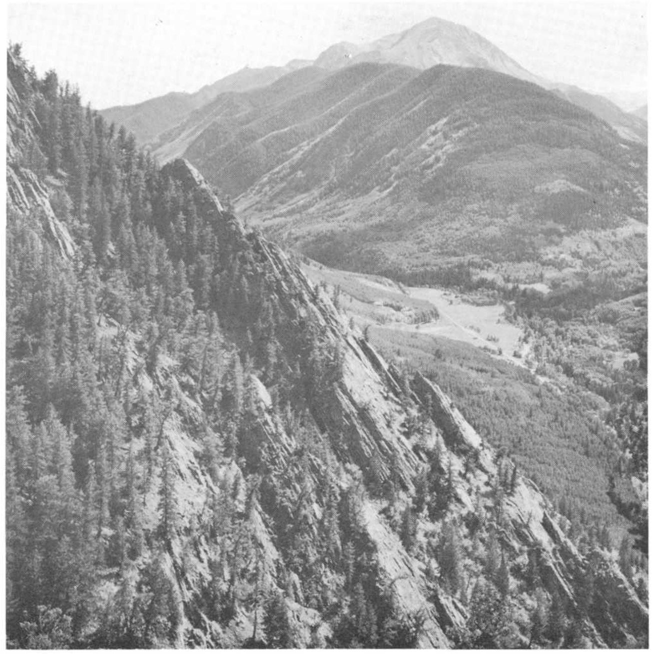


Figure 24. Steeply dipping Pennsylvanian-Permian red beds along east side of Castle Creek just south of junction with Conundrum Creek. These beds were tilted in the latest part of the Cretaceous and earliest part of the Tertiary when the Sawatch Range, lying to the east (left side of the photograph), was uplifted. View toward south. The bare mountain in the middle of the photograph is granodiorite faulted against red beds underlying the wooded ridge. The meadow in the valley bottom was the site of Highland, a short-lived prospecting camp in the early 1880's.

Thirdly, all the sedimentary strata near Aspen are broken by a system of faults that runs mainly north and south along the edge of the Sawatch uplift, and most rich ore deposits occur near intersections of these faults with the permeable unconformities. These faults resulted from the stretching and bending of rock layers at the margin of the uplift. One long, continuous fault zone in the system lies west of most of the orebodies, passes beneath the western part of Aspen, and runs directly up the valley of Castle Creek (fig. 15). Hence it is called the Castle Creek fault zone.

It should be noted here that a fault zone is simply an area where the rocks have broken and shifted position at some time in the past. Along some fault zones, such as those in California, the movement may have been as recent as last week. But the Castle Creek fault zone has not moved in millions of years and poses little threat to Aspen or its residents.

Yet the rocks along this zone bear testament of a time when it was not so harmless. Red beds of the Maroon Formation have been tilted steeply along the east side of Castle Creek (fig. 24). The northwest end of Aspen Mountain (locally called Shadow Mountain; fig. 17) is a geological jigsaw puzzle, which has dozens of

Figure 25. Overturned Mesozoic rocks in fault slice along Castle Creek fault zone on Red Butte, viewed northeast from Colorado 82 just northwest of Aspen. Rocks dip into the hill and older rocks overlie younger rocks. The rocks were first folded and then faulted while the Sawatch Range was uplifted at the end of the Cretaceous and the beginning of the Tertiary. Cross faults with small displacements cut the beds. From youngest to oldest, the rocks are: Mancos Shale, Km; Dakota Sandstone, Kd; Morrison Formation, Jm; Entrada Sandstone, Je; Chinle Formation, TRc; State Bridge Formation, TRPs. Note offset of the Chinle Formation, across the fault.

faults slicing through it. And at Red Butte, just northwest of town, the rocks have been overturned so that Triassic and Jurassic formations now lie above Cretaceous strata (fig. 25).

Beyond Red Butte, the Castle Creek fault zone trends northwest, apparently following a zone of weakness that developed in the Paleozoic strata during the time of the Ancestral Rockies. It parallels the southeast-northwest trend of those earlier ranges that had dominated the area 100 million years before the rise of the Sawatch uplift.

The phenomenally rapid rise of this more recent uplift continued until about 65 million years ago. At that time the uplift extended uninterrupted from Aspen to the vicinity of Fairplay, for the upper Arkansas valley did not yet exist. (See p. 49).

Near the crest of the uplift, unrelenting mountain streams stripped away the thick upper Paleozoic red beds and cut deeply into the thin lower Paleozoic strata; they eventually exposed the hard, crystalline Precambrian rocks that had formed a billion and a half years earlier.

From the time the first few thin layers of Sawatch Quartzite collected on the floor of the advancing Cambrian sea until the time when the retreating shoreline of a quite different sea deposited the thick sandstones of the Mesaverde Formation was a span of some 460 million years. Yet all the ancient rock strata that accumulated during this period—about 20,000 feet of rock— were uplifted and stripped away in little more than 5 million years. In this case, erosion worked 90 times faster than deposition!

For the period from 65 to 35 million years ago, no record of geologic events in the Aspen area has been preserved. We assume that the Sawatch uplift was eroded by stream action during this time, much as it is today. Some of the debris that washed off the uplift came to rest in conglomerate beds of this age now found in the Piceance Creek basin, about 35 miles west of Aspen. The conglomerate beds grade upward into finer grained rocks, reflecting the gradual wearing down of the uplift.

By middle Eocene time (about 45 million years ago), the uplift was very worn and probably stood much lower than it does today. Streams running off the uplift flowed into a large lake—Lake Uinta—which straddled the borders of Colorado, Utah, and Wyoming during Eocene time. Fossil remains show that the lake abounded with fish, birds, crocodiles, and turtles, for a subtropical climate then prevailed in this part of North America. More important, though, were the trillions of microscopic plants that flourished in its warm waters; they settled into the bottom mud and decayed, thereby forming the largest oil-shale deposit on the continent. The oil-shale beds are now included in the Green River Formation, which extends through a large area of northwestern Colorado and its neighboring States.

Molten Rock, Uplift, and Erosion

At the beginning of the Oligocene Epoch (about 35 million years ago), hot magma from deep within the Earth once again invaded the rocks of western Colorado. In many parts of the State, the molten rock broke through the surface layers and spread thick deposits of lava and volcanic ash on the surrounding countryside. Ninety miles south of Aspen, the San Juan Mountains were being formed in an area that had been mostly flat and low. The San Juans were not pushed up from beneath, as the Sawatch uplift was; rather, they were built up layer by layer on top of the preexisting rock. Forty miles southwest of Aspen, the West Elk Mountains were formed in much the same manner.

It is not known whether any of this volcanic rock ever covered the site of Aspen. Any that might have been there has by this time worn away. The place closest to Aspen where volcanic rocks are now found is on the crest of the Sawatch Range south of Independence Pass, where a small volcano evidently spouted briefly during the Oligocene and then collapsed. Other remnants are found near Mount Sopris.

Much of the magma that intruded near Aspen at this time never reached the surface. Molten rock that pushed toward the surface south and west of Aspen intersected the fault plane along which the Elk Mountains thrust sheet had slid 35 million years earlier. The magma then spread out in a thick, irregularly shaped layer along the fault plane rather than continuing upward.

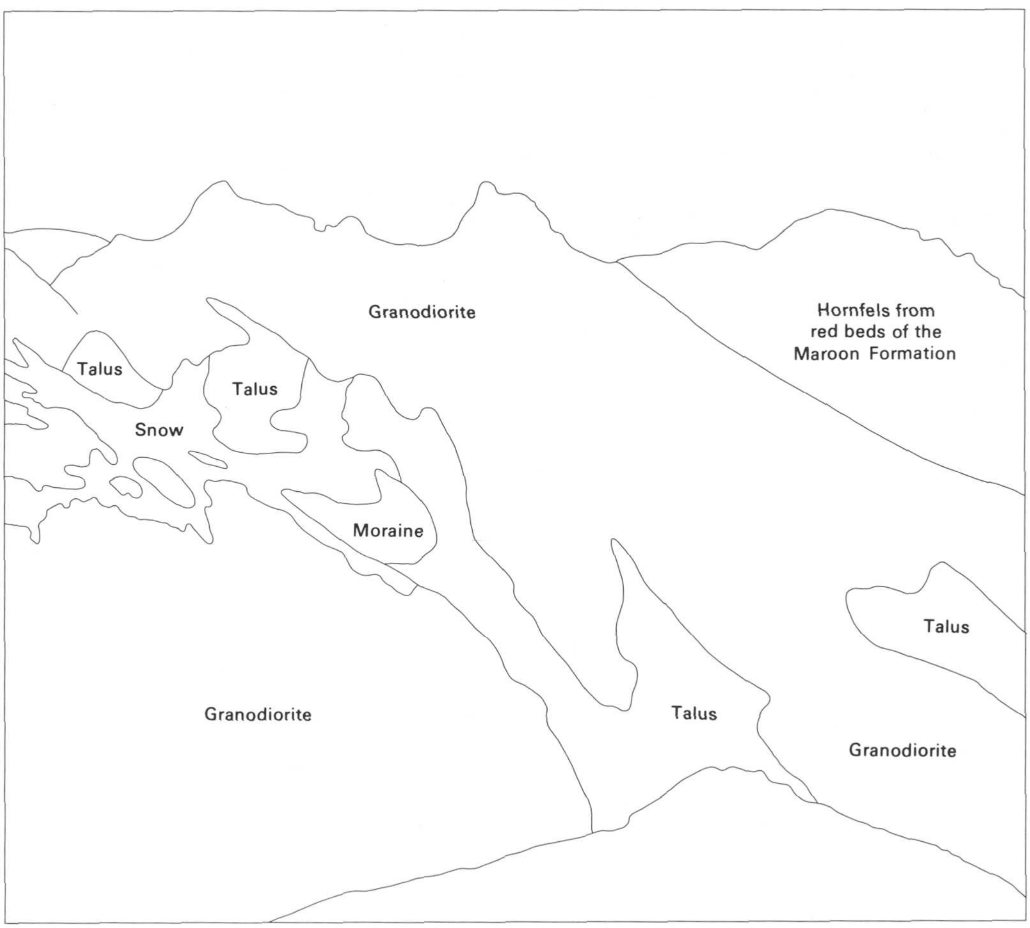
Large intrusions of this sort—called *plutons*—formed in two places near Aspen. One is about midway between Aspen and Crested Butte; the other lies about 15 miles west by southwest of Aspen, around Snowmass Mountain. The first of these, the White Rock pluton, which forms White Rock Mountain, is shaped something like a doughnut in map plan and is about 10 miles across (fig. 15). The other body, the Snowmass pluton, is roughly oval shaped and is about 8 miles wide, east to west. Both plutons have been dated as 34 million years old. When these two bodies intruded, they pushed up the thick, overlying red beds so far that another new mountain range was created: the Elk Mountains. These mountains were boosted some 3,000 to 4,000 feet above the surrounding area.

The rock formed from this magma (granodiorite) is white to light gray, like much of the older igneous rock in the area. It is chiefly distinguished from the surrounding sedimentary rock by its lack of structure. It does not form in thin layers, but rather in amorphous masses.

Most of the igneous rock now found in the Elk Mountains formed from the Oligocene granodiorite magma that created this range. In some places the intruding masses pushed in along the bedding of the preexisting strata; in others they punched up through the beds in an irregular fashion (fig. 26; pl. 1,*A* and *B*). In addition to forming Snowmass and White Rock Mountains, for which the two large plutons were named, the granodiorite now forms Taylor, Star, Keefe, and Capitol Peaks and many unnamed summits in the area.

When the magma intruded along the fault plane beneath the Elk Mountains thrust plate, its searing heat (more than 1,100 degrees F) dramatically affected the adjacent rocks. The rocks of the Maroon Formation changed color near the magma (fig. 27). The discoloration was most intense where the heat was greatest, close to the contact with the granodiorite, but in some places the alteration in the red beds is distinct a mile or more from the contact. The layers of red sandstone and siltstone were metamorphosed to quartzite and to a dense, hard, fine-grained, greenish-gray rock called *hornfels*.

The great heat had caused a partial reversal of the process by which these rocks first acquired their red color. Basically, some of the iron in the rocks changed its chemical form (valence), and some of the oxygen it had earlier absorbed was driven off. As a result, the red hematite (the "rust") was transformed to black magnetite. Some of the iron also joined with calcium, aluminum, and silicon from other minerals in the sediment to form minerals such as pyroxene and amphibole, which are primarily responsible for the greenish tinge of the hornfels. Most of these minerals are difficult to see, for they form grains no larger than the head of a pin, but directly adjacent to the granodiorite some crystals are as much as a quarter of an inch long.


Granodiorite
Hornfels from
red beds of the
Maroon Formation
Talus
Talus
Snow
Moraine
Talus
Granodiorite
Talus
Granodiorite

Many of the high peaks south of Aspen are made of this greenish-gray hornfels, including Castle Peak, Hayden Peak, and Hunter Peak; also, the lower part of Maroon Peak has been changed to hornfels, although the higher beds retain their famous red color (fig. 28; pl. 1, *A* and *B*). The hornfels is also visible at many places in Montezuma Basin, along the road to Pearl Pass, and on the trail over Electric Pass.

About 3 million years after the White Rock and Snowmass plutons were formed, more granodioritic magma made its way into the rocks of the Elk Mountains. The volume of magma was much less in this second episode, and the amount of heat transmitted was not enough to cause much metamorphism. The rock formed in this episode is called *porphyritic granodiorite*, because it contains many large crystals (an inch or more in length) of feldspar and other minerals embedded in a fine-grained matrix.

This type of rock forms prominent *sills* (thin, horizontal layers) between the beds of the Maroon Formation north of Maroon Lake. Another, larger sill forms rugged cliffs along the east side of Snowmass Creek valley (fig. 29); it has yielded a radiometric age of 31 million years. Some of the magma invaded fractures in the red beds and in the newly formed granodiorite of the large plutons to solidify as vertical *dikes*. Many light-gray dikes of this age are conspicuous in the red rocks of Snowmass Creek valley and nearby Minnehaha Gulch. In places, porphyritic granodiorite magma pooled, pushing up the overlying strata and forming thick, lens-shaped bodies called *laccoliths*. (See fig. 30.)

Again, during the cooling of these igneous rocks, downward circulating ground water became superheated and dissolved small amounts of metal, sulfur, silica, and other substances. The water carried these elements up into cooler rock and deposited them in fractures in already cooled granodiorite or in overlying sedimentary rocks to form *veins*. A few of these veins have been mined for silver and lead. The most famous mine in a vein of this age is the Montezuma mine near Castle Peak, which was once owned by silver magnate H.A.W. Tabor, a famous figure in Colorado mining history.

◄ **Figure 26 (facing page).** Granodiorite on the left and in the center has intruded Pennsylvanian-Permian red beds of the Maroon Formation that make up two peaks at right. The heat of the molten intruding rock changed the red beds to green and gray hornfels and quartzite. Notice the difference between the shapes of the mountain slopes formed by the massive igneous rock and those formed by the bedded sedimentary rock. The small, inconspicuous ridge below the snowfield just left of center is a moraine of a glacier that probably melted since Aspen was first settled. View from 13,700-foot altitude on northeast shoulder of Castle Peak on the most used route of ascent. Cathedral Peak is on right skyline.

Near the head of Cooper Fork, 12 miles south of Aspen, interactions between hot solutions from the granodiorite and limestone in the surrounding rock caused iron ore to replace some of the limestone. Miners extracted this ore from an open pit more than 12,000 feet above sea level in the 1960's and 1970's.

In places, the hot circulating solutions permeated the cooling granodiorite and adjacent rock along small, closely spaced fractures and even between grains of minerals to form disseminated deposits. In these deposits, iron sulfide (pyrite; sometimes called fool's gold), copper sulfide (chalcopyrite), and molybdenum sulfide (molybdenite) are distributed throughout the rock rather than being concentrated in well-defined veins. Pyrite is the most abundant mineral in the disseminated deposits; this iron-bearing mineral turns to iron oxide ("rust") wherever it has been exposed to moisture, which gives the surface exposures of the rock an obvious rusty-brown color. Two large areas of rusty weathering rock are on East Maroon Creek west of Hunter Peak and along the Cataract Creek valley and the adjacent part of the Conundrum Creek valley (pl. 1*B*). So far, none of the ore deposits associated with Oligocene igneous rocks south of Aspen have proved to be as valuable as the older deposits close to the city.

Both the porphyritic granodiorite and the earlier fine-grained variety may have come from a great magma reservoir that is thought to have lain just a few miles beneath the Colorado mineral belt. Indeed, some slight variations in the strength of the gravitational field near Aspen have been interpreted as indications of the presence of a large mass—a batholith—of now-crystallized igneous rock. Such a reservoir could have been the source not only of the Oligocene granodiorites, but also of all the molten rock that invaded the Aspen area from the end of Cretaceous time to the present. However, such a batholith, if present, may represent just a way station for the rising molten rock, for the chemical compositions of Tertiary igneous rocks from this area seem to indicate that the magma originally formed 150 miles or more beneath the surface.

The late part of the Tertiary Period (25 to 2 million years ago) was a time of erosion in the Aspen area and throughout western Colorado. No sedimentary rock of this age is now found near Aspen, although some thick stream gravels occur on the opposite side of the Sawatch Range in the upper Arkansas River valley. Some lake beds of late Tertiary age are intermingled with stream deposits in Middle Park (northeast of Vail) and in the San Luis Valley, and others are interbedded with basalt flows on The Flat Tops north of Glenwood Springs.

Those basalt flows were a product of late Tertiary volcanic activity, which was much more restricted than that of the Oligocene. Two types of magma invaded western Colorado in the late Tertiary. One contained much more silica than the Oligocene magma and formed

Figure 27. Cathedral Lake and Cathedral Peak from east. Light-gray-green and dark-gray hornfels caused by baking of Pennsylvanian-Permian red beds. Some rocks just to the right of the lake retain their red color. Small faults offset beds on the left side of Cathedral Peak and on the ridge to the left of the peak. Much talus and three rock glaciers cover lower slopes and valley bottom.

rocks that were lighter, both in weight and in color, than those earlier rocks. The second type contained much less silica and formed rocks that were both heavier and darker than the Oligocene igneous rocks. The lighter rocks that reached the surface, either through volcanoes or through fissures, are called *rhyolite*; those that formed beneath the surface are granite. The corresponding types of dark-colored rocks are *basalt* and *gabbro*

The appearance of this bimodal sequence of igneous rocks in the geological record is believed to signal a change in the stress patterns in the crust in this part of the continent. During and after the Laramide orogeny, from about 70 to 25 m.y. ago, compressive stress predominated, but since then stress has been extensional, tending to pull apart the crust. The regional crustal extension caused dramatic effects in many parts of the West, which will be described on page 49.

In the late Tertiary, as in the Oligocene, the igneous rocks that formed close to Aspen were of the subterranean, *intrusive* type. Small dikes of gabbro and similar dark rocks cut through the lighter colored granodiorite of the White Rock and Snowmass plutons. They are thought to be Miocene and Pliocene in age (about 25 to 2 million years old). Twenty miles southwest of Aspen, about 12 million years ago, a light-colored granite pluton pushed up through strata ranging in age from Precambrian to Cretaceous and lifted them up around its edges. Subsequent erosion has revealed a granite-cored, dome-shaped structure 5 miles across, called the Treasure Mountain dome (fig. 15).

North, south, and west of the Aspen area, the volcanic or *extrusive* forms of these rocks are more common. Thin sheets of basalt and rhyolite in many areas of the San Juan Mountains cover the older, thicker volcanic rock. Elsewhere, dark-colored basalts erupted from fissures 25 to 10 million years ago and spread out along the floors of broad valleys and basins. Ironically, these same basalts now cover the tops of high plateaus and mesas, for they were more resistant to erosion than the adjacent sedimentary rocks. As mentioned above, such basalts cap The Flat Tops north of Glenwood Springs, and others lie atop a much lower ridge near Cottonwood Pass. Basalts a few million years younger than these poured out in a broad valley eroded in soft Pennsylvanian evaporites to form the plateau known as Missouri Heights northeast of Carbondale.

A series of basalt flows atop a hill northwest of Woody Creek (pl. 1 C) includes the youngest igneous rocks yet known in the Roaring Fork valley; they have been dated as 1.5 million years old. Hence these basalts are younger than the oldest glacial moraine atop Red Mountain near Aspen, and they belong not to the Tertiary Period, but to the Pleistocene Epoch. The basalts overlie stream gravels that must have been deposited by the Roaring Fork River in the early Pleistocene, yet these

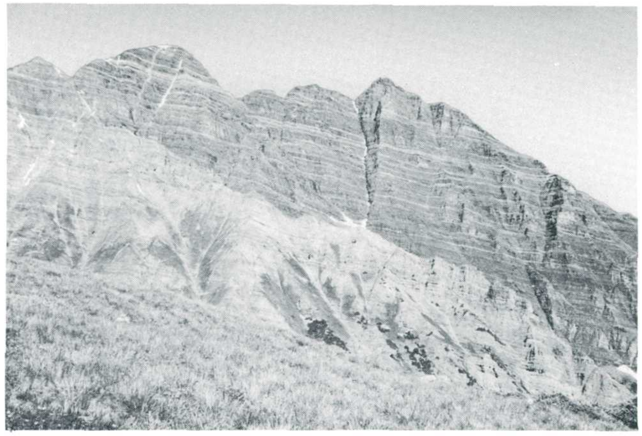


Figure 28. Pennsylvanian-Permian red beds on Maroon Peak (left) and North Maroon Peak (right) baked to hornfels (light gray in lower part of cliffs) by granodiorite intrusive that crops out in the valley bottom of West Maroon Creek below this view. Lighter colored beds on peaks are coarse-grained sandstone and conglomerate; darker beds are fine-grained sandstone and siltstone. A thin dike cuts the red beds at the summit of Maroon Peak. View from the southeast.

Figure 29. A large sill of porphyritic granodiorite (the gray rock) intrudes red beds of the Maroon Formation along the east side of Snowmass Creek valley. The sill is 2,000 feet thick and more than 5 miles long and contains conspicuous crystals of potassic feldspar.

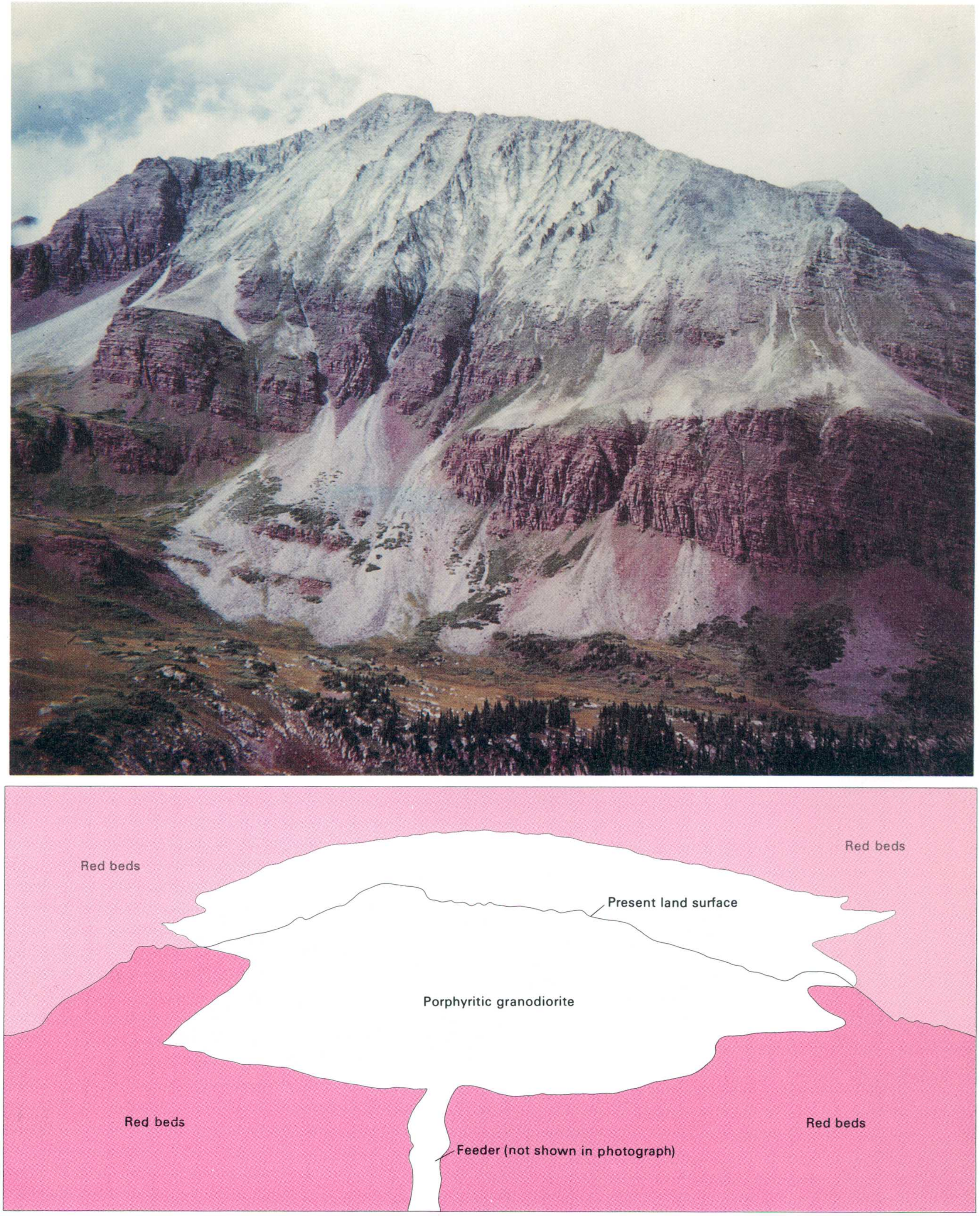


Figure 30. Laccolith of porphyritic granodiorite forming top of mountain north of Willow Lake. Light-colored igneous rock lies on Pennsylvanian-Permian red beds, which are metamorphosed only in a very thin zone directly adjacent to the intrusive. The bottom of the laccolith is approximately parallel with the bedding in the red beds, except where it cuts the bedding on the left side of the photograph. The roof of the intrusive has been removed by erosion. The sketch shows the probable original shape of the laccolith and the part now preserved and shown in the photograph. Notice that talus composed of white intrusive rock has come downslope over the red beds.

gravels are now 1,200 feet above the bed of the Roaring Fork. The remarkable downcutting by this river over the last 2 million years has been mentioned previously. (See p. 20).

The Roaring Fork is not unique in this respect. Streams throughout the Western United States have cut amazingly deep channels in the last 10 million years or so. The mile-deep gorge of Arizona's Grand Canyon was excavated during this geologically brief period. One contributing factor must have been the great volume of water carried by western rivers during the ice age; but the most important cause of the downcutting is the steady, rapid uplift of the entire western region during this period. The uplift apparently began in early Miocene time, and it has affected all the land from the Great Plains to the Pacific Coast, raising most of this area 3,000 to 5,000 feet.

From the Southern Rocky Mountains to southern California, the regional uplift was accompanied by regional extension of the crust. (See p. 46.) The land in this area was pulled apart into large blocks as it rose. Some blocks were thrust up high by the regional uplift; others remained low, or did not rise as much. The effects of these processes dominate the scenery from Salt Lake City to the Sierra Nevada, where many individual mountain ranges are separated by broad basins containing gravel, sand, and silt washed from the ranges.

In Colorado, the effects of simultaneous uplift and extension were less widespread but just as dramatic. East of Aspen, in the eastern part of the Sawatch uplift, a long block about 6 miles wide and 50 miles long did not rise as much as the surrounding land. In comparison to the rest of the uplift, this block appears to have subsided, although it actually may be higher now than it was in early Miocene time. The resulting steep-sided fault-block valley is now occupied by the upper course of the Arkansas River. Streams rushing down the steep eastern face of the modern Sawatch Range have already deposited thick layers of Pliocene and Pleistocene sediments in the valley. The isolated eastern edge of the old Sawatch uplift is now the Mosquito Range.

Miocene and Pliocene subsidence features such as those in the upper Arkansas valley are also well developed in the San Luis Valley and southward along the Rio Grande through New Mexico. Apparently, the Earth's crust has been fractured and pulled apart along this zone, which is known as the Rio Grande rift. No clear-cut evidence of such differential uplift and subsidence has been found along the west side of the Sawatch Range near Aspen. Such movements would be difficult to detect, though, as no rocks of late Tertiary age are found in the area. The gentle, uninterrupted grade away from the Sawatch Range along the flat interstream divides (see p. 13 and pl. 1 C) suggests no major fault movement of this age. However, 10 miles south of Aspen, a nearly vertical fault along the east edge of the White Rock pluton coincides with a steep cliff, and this coincidence could indicate either that vertical movement occurred relatively recently on this fault or that the rocks east of the fault were much less resistant to erosion than those west of the fault.

The uplift of Miocene and Pliocene time set the scene for the final chapter in the geologic development of the Aspen region, the chapter that we have called The Story of the Land. Ice, water, and gravity have carved and molded the land around Aspen in the last 2 million years, but all the events of the preceding 1.8 *billion* years had a strong influence on the final configuration of the Aspen area. Were it not for the ancient layers of schist and gneiss, the thin sediments of the early Paleozoic sea, the thick Pennsylvanian through Triassic red beds, the Cretaceous shales and sandstones, and the igneous intrusions of Tertiary time, the Aspen area would be a quite different place today.

Geology and Land-Use Planning in Aspen

Geologic information is one of the basic requirements for effective regional land-use planning. The kinds of rocks and their distribution, the physiographic features, the streams and their history, all directly or indirectly affect or even control the way man lives, and man must have a good understanding of these things to live most wisely in any area. All of these are integral parts of good land-use planning. For example, geologic study of an area can reveal the presence of hazardous conditions such as landslides, avalanches, flood areas, and unstable soils. It can also provide important economic information, such as the availability of potable water, ease of excavation, availability of suitable construction materials, and value of mineral resources in the rock.

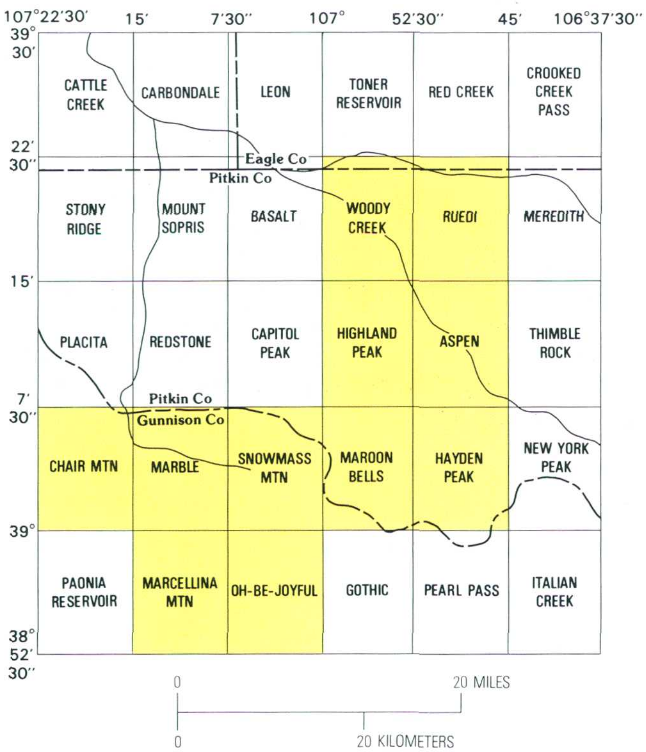


Figure 31. Index map showing U.S. Geological Survey 7½-minute topographic quadrangle maps for areas near Aspen. These maps accurately represent the shape and altitude of the land and the courses of the streams. They show roads and houses existing at the time the maps were made (in the 1960's for most of the quadrangles). Because these maps are made primarily from aerial photographs, locations of trails are not everywhere accurate. Yellow quadrangles are covered by geologic maps listed in the text.

No two areas are alike, and the environmental geologic factors that are important in one place may be of no consequence in another. To focus the attention of concerned individuals, government units, or business enterprises on the basic and important factors of geology that affect a certain area, many special-purpose maps are made that relate to those local problems in ways that are directly useful. A series of such maps has been prepared for the area surrounding the city of Aspen, and they are listed in the following references and in figure 31.

Modern, detailed geologic maps in the Aspen region.—(7½-minute quadrangles, scale 1:24,000. U.S. Geological Survey Geologic Quadrangle Maps:

GQ–511 Marcellina Mountain
GQ–512 Marble
GQ–578 Oh-Be-Joyful
GQ–704 Chair Mountain
GQ–788 Maroon Bells
GQ–853 Snowmass Mountain
GQ–863 Hayden Peak
GQ–932 Highland Peak
GQ–933 Aspen
GQ–967 Woody Creek
GQ–1004 Ruedi

Folio of the Aspen 7½-minute quadrangle.—Each map shows one factor in the environment of the Aspen quadrangle. U.S. Geological Survey Miscellaneous Investigations Maps:

I-785–A Potential geologic hazards
–B Ground-water potential
–C Relative ease of excavation
–D Mines, prospects, and areas of significant silver, lead and zinc production
–E Slope
–F Relative permeability
–G Avalanche areas
–H Types of bedrock and surficial deposits

Additional Reading

Readings on Local History

Bancroft, Caroline, 1967, Famous Aspen, 6th edition: Boulder, Colo., Johnson Publishing Company, 56 p.

Brief and lively account, about half of which deals with the modern revival of Aspen as a recreational and cultural center.

Shoemaker, Len, 1973, Roaring Fork Valley, an illustrated chronicle: Denver, Sundance Ltd., 216 p. (Originally published in 1958.)

The author grew up in the Roaring Fork valley during the silver-mining days and worked for the U.S. Forest Service in the region. Most of the book covers the period before 1900. Historic and modern photographs.

Wentworth, F. L., 1976, Aspen on the Roaring Fork, 3rd edition: Denver, Sundance Publications Ltd., 192 p. (Originally published in 1935.)

The author lived in Aspen a few years during the height of the silver boom and returned 32 years later. He lived there summers in the 1930's. Contains two rambling accounts by first settlers. Many historic photographs.

Technical Reports on Geology

Bryant, Bruce, 1979, Geology of the Aspen 15-minute quadrangle, Pitkin and Gunnison Counties, Colorado: U.S. Geological Survey Professional Paper 1073, 146 p.

Technical report on the general geology of Aspen region based on detailed mapping in the 1960's.

Holmes, W. H., 1876, Report on the geology of the northeastern portion of the Elk Range, Chapter 6 *of* Report of F. V. Hayden, U.S. Geologist, *in* Hayden, F. V., Eighth Annual Report of the U.S. Geological and Geographical Survey of the Territories*** for the year 1874: Washington, U.S. Government Printing Office, p. 59–71.

The first published report containing a geologic map based on reconnaissance including the Elk Mountains as far west as the Crystal River and north to the Roaring Fork. This report, those by Hayden in the same volume and in the Seventh Annual Report, and those by Peale in the latter contain superbly picturesque descriptions of the country and the geology, early observations and interpretations, cross sections, and precise pen-and-ink drawings.

Knopf, Adolph, 1926, Recent developments in the Aspen district, Colorado: U.S. Geological Survey Bulletin 785, p. 1–28.

Extends Spurr's (1898) mapping south of the Midnight Mine into the Hayden Peak quadrangle, describes the Hope and Midnight Mines, and gives petrographic descriptions of the igneous rocks.

Spurr, J. E., 1898, Geology of the Aspen mining district, Colorado: U.S. Geological Survey Monograph 31, 260 p.

One of the classic mining district studies of the early period of the Geological Survey. Includes general geology of the Aspen 7½-minute quadrangle, detailed maps of the mined areas, and descriptions of individual mines.

Vanderwilt, J. W., 1935, Revision of the structure and stratigraphy of the Aspen district, Colorado, and its bearing on the ore deposits: Economic Geology, v. 30, p. 223–241.

Application of more modern stratigraphy and the concept of D. F. Rohlfing, a mining geologist and engineer who lived and worked in Aspen over a period starting in the 1880's, before Spurr's study, and who was still active during the 1930's, to the occurrence of ore in the mining district. Some discussion of regional geology.

Other Publications Containing Brief Accounts of the Geology Around Aspen and Information on Roads, Trails, and Wildlife

Laing, David, and Lampiris, Nicholas, 1980, Aspen high country, the geology, A pictorial guide to roads and trails: Aspen, Colo., Thunder River Press, 132 p.

Wyrick, Ken, Ware, J. B., and others, 1978, Hiking guide to Aspen: Aspen, Colo., Aspen Editors, 159 p.

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[Numbers shown in **boldface** denote pages that include relevant illustrations. Page numbers in *italic* designate the most important text reference]

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Bryant and Martin—THE GEOLOGIC STORY OF THE ASPEN REGION—U.S. Geological Survey Bulletin 1603

U.S. DEPARTMENT OF THE INTERIOR

March 3, 1849