TRAILS THROUGH TIME: A GEOLOGIST'S GUIDE TO JEFFERSON COUNTY OPEN SPACE PARKS

INTRODUCTION

Jefferson County straddles one of the most conspicuous and important geographic and geologic boundaries in western North America, the eastern flank of the Rocky Mountains. To the east you can travel 1,100 miles across Great Plains and Central Lowlands before you sight the western foothills of the Appalachians. If you travel in the other direction you will cross or skirt mountain range after mountain range until you sight the Coast Range near San Francisco, more than 900 miles to the west. Many of these mountains have different ages and origins than the Colorado mountains, but they are all part of the great mountain belt called the North American Cordillera that extends along the western edge of the continent from Alaska through Mexico.

What is the reason for the remarkably straight and abrupt eastern flank of the Colorado Front Range? The brief answer is that it marks the edge of a block of ancient metamorphic and igneous rocks that has been uplifted relative to younger flat-laying sedimentary rocks that underlie the plains to the east. During the uplift, the sedimentary rocks along the boundary have been uplifted and tilted eastward to form the discontinuous line of hogback ridges that parallel the mountain front. Erosion during and after the uplift has removed the sedimentary rocks that once lay above the harder rocks of the mountain uplift, carved the scenic peaks and mountain canyons in the hard crystalline rocks of uplifted block, and worn away the softer layers of sedimentary rocks of the plains, but left a few of the harder upturned layers along the mountain front as hogback ridges.

Jefferson County Open Space Parks, as well as other nearby parks and National Forest lands, offer marvelous opportunities to explore the geologic story behind this singular landscape. At first the distribution of rocks of different ages and types seems almost random, but careful study of the rocks and landscape features reveals a captivating geologic story, a history that tells of the building of the foundations of the continent, the rise and destruction of long-vanished mountain ranges, the ebb and flow of ancient seas, and the constant shaping and reshaping of the landscape in response to the never-ending interplay between uplift and erosion. This historical account is constantly being improved and expanded as new evidence accumulates and new interpretations evolve.

THE LONGER STORY

Chapter 1: The Basement Rocks

The metamorphic and igneous rocks that make up the uplifted mountain block are collectively called basement rocks, because all of the younger sedimentary strata rest on them. The metamorphic rocks are chiefly mica schist and various types of layered gneiss, and locally, marble and quartzite. They were formed between about 1,800 and 1,600 million years ago when sedimentary and volcanic rocks, which originally lay at the Earth's surface, were carried down, some to depths of 7 or 8 miles, and subjected to temperatures of as much as 800^{o} to 900^{o} F. Under these extreme conditions many of the original minerals reacted with one another to form new minerals characteristic of metamorphic rocks, while minerals stable at these depths and temperatures formed larger and more conspicuous mineral grains and aggregates. At the same time most of the rocks were intensely deformed by plastic flow so that almost all of their original sedimentary and volcanic features were obliterated. The metamorphic rocks in Jefferson County were invaded by large bodies of granite and related plutonic igneous rocks during three episodes of igneous intrusion: once between 1,720 and 1,685 million years ago, during or shortly after their formation; again between 1,425 and 1,420 million years ago, and finally about 1,100 million years ago. The older granitic rocks are widespread in the northern part of the county northwest of Ralston Creek; 1,425 to 1,420 million year old granitic rocks crop out in extensive areas south and southwest of Evergreen; and the younger granitic rocks underlie most of Jefferson County south of U.S. Highway 285 and extend further south where they makes up Pikes Peak.

MILLIONS AND BILLIONS

A million is a thousand thousands (1,000,000) or in scientific notation 1x10^6. A billion is a thousand million (1,000,000,000) or in scientific notation 1x10^9. One million dimes would make a stack 0.8 mile high; a billion dimes would make a stack 800 miles high! This should give a feel for both the length of geologic time and the size of the federal budget.

The metamorphic rocks and the granitic rocks of the first episode of igneous intrusion are part of an extensive area of similar basement rocks of the same general age that crop out throughout Colorado, New Mexico, Arizona, and parts of Nevada and which have been found by deep drilling beneath younger sedimentary rocks in eastern Colorado, Nebraska, and Kansas. The most ancient rocks exposed in the bottom of the Grand Canyon are part of this group of basement rocks. Many geologists believe that the sedimentary and volcanic rocks from which the metamorphic rocks formed were deposited as a series of chains of volcanic islands and intervening basins that were jammed against the southern edge of North America by plate tectonic movements between about 1.8 and 1.6 billion years ago. Recently, however, several geologists have questioned whether plate tectonics in the modern sense even operated that early in Earth's history. Thus, the origin of these basement rocks is still a matter of serious debate.

The 1,420 to 1,425 million year old granitic rocks are part of a broad belt of similar intrusions that extends from southern California to Newfoundland. The origin of this extensive belt of granite intrusions is still a mystery—many explanations have been offered, but none is widely accepted. The 1,100 year old Pikes Peak Granite is also a puzzle. No granitic rocks of this age are exposed anywhere else in the Rocky Mountains.

Chapter 2: The Missing Chapter

If we insist on limiting our story strictly to evidence we can find in the rocks of Jefferson County, we will see no clues to what transpired between emplacement of the 1,100 million year old granite and the deposition of the oldest of the sedimentary strata upturned along the mountain front, which were deposited about 320 million years ago, a hiatus of 790 million years. However, if we venture outside our own backyard, to other parts of Colorado or even to other parts of the world we find evidence of some of the major events that occurred during that enormous span of time.

Geologists have recently realized that rocks of the same age and character as the 1,800-1,600 basement rocks of Colorado make up much of the Transantarctic Mountains in East Antarctica and that bodies of granite identical to the approximately 1,400 million year old granite bodies in Colorado are also found there. This strongly suggests that 1,400 million years ago the block of continental crust that was ultimately to become East Antarctica was nestled against the block that was to become North America. It is a long way from the Front Range to the Transantarctic Mountains (about 8,500 miles)., but if the plates were moving apart at the rate that the North America plate is currently moving (about an inch per year), the journey could have been accomplished in about 250 million years. East Antarctica began pulling away from North Americas as early as 1,200 million years ago; by about 700 million years ago the separation was complete, and East Antarctica began its long and circuitous journey toward the South Pole.

As the continents pulled apart, the western edge of North America began to subside and warm shallow seas lapped eastward far across the sinking continental margin, which by that time had been eroded to a gently rolling plain. Between about 500 and 320 million years ago (during the Cambrian, Ordovician, Silurian, Devonian, and Mississippian geologic periods) layers of sandstone, shale and limestone were deposited in this seaway, forming an extensive blanket a few hundred to more than a thousand feet thick that covered most of the Rocky Mountain region, including Colorado (Silurian rocks were deposited across much of Colorado, but were removed by erosion prior to deposition of the overlying Devonian strata). These rocks are spectacularly exposed in Glenwood Canyon. They also crop out as tilted layers along the eastern flank of the Front Range in the Garden of the Gods and in areas to the south, but are not found farther north in the Front Range. The reason for their absence is discussed in the next chapter.

Chapter 3: The Ancestral Rocky Mountains - The Mountains No One Knew

About 320 million years ago (in the Pennsylvanian geologic period) plate tectonic movements during the assembly of the supercontinent Pangea brought North America together with South America and Africa. One of the results of this convergence was the uplift of great mountain ranges in the Colorado region. These ancient mountains are called the Ancestral Rocky Mountains. The ranges of the Ancestral Rockies are now completely destroyed by erosion. However, thick deposits of red conglomerate, sandstone, and shale (collectively known as redbeds) made up of material eroded from them and deposited in the flanking basins attest to their existence. These deposits are now widely exposed in some of Colorado's most spectacular modern ranges, including the Elk Mountains and the Sangre de Cristo Range. On the eastern flank of the Front Range they form the Flatirons near Boulder, and the spectacular outcrops at Ralston Buttes, Red Rocks Park, and Roxboro State Park. In the Jefferson County segment of the modern mountain front the redbeds (here known as the Fountain Formation) rest directly on the eroded surface of the basement rocks. The reason that the older sedimentary strata of Chapter 2 are missing is that this segment of the modern Front Range was part of one of the Ancestral Rocky Mountain uplifts. As the ancestral Front Range rose, the Early Paleozoic sedimentary rocks that once blanketed the basement were stripped off the uplifts by erosion, exposing the basement rocks beneath. The exposed basement rocks were ultimately buried by the Fountain Formation, which is composed of debris shed from the higher parts of the uplift.

The Ancestral Rockies were probably just as rugged as our modern mountains, but their bases were essentially at sea level. They were at least in part covered by forests of tree ferns (flowering plants had not yet evolved). Whether or not they reached timberline is problematic. There is clear evidence of widespread glaciation at this time in the southern parts of Pangea, but there is no direct evidence that there were glaciers in the Ancestral Rockies, which lay very close to the equator. In fact, the climate was probably warm and arid or semi-arid.

Like all mountain uplifts, the Ancestral Rockies uplift was under constant attack by erosion. As the uplift slowed and stopped, erosion continued, ultimately completely destroying the mountain ranges, leaving behind only their wreckage.

Chapter 4: The Great Cretaceous Seaway

By about 250 million years ago the Ancestral Rockies had been leveled and extensive layers of sandstone, shale, and limestone were deposited across their eroded stumps in the Triassic and Jurasic Periods of the Mesozoic Era. These deposits were laid down on land as windblown desert sand and deposits of sand and mud along sluggish meandering streams or in shallow lakes. About 115 million years ago, in the Cretaceous Period, waters of a shallow sea began to spread westward across the future site of Colorado. Eventually the advancing waters spread to form a great seaway that covered as much as one third of North America. The warm shallow waters teemed with life, including fish, mosasaurs (huge swimming lizards), sea turtles, and ammonites (spiral-shelled free floating mollusks). Dinosaurs of many species prowled along the beaches and flanking lowlands, while pterodactyls (fish-eating flying reptiles related to dinosaurs) circled overhead.

Sand in beaches, on bars, and in dunes along the western shores of the encroaching seaway was later buried and solidified to form the Dakota Sandstone, the hard erosion-resistant layer that now forms the prominent hogback east of the mountain front. As the waters of the advancing seaway deepened, deposits of black mud, now preserved as thousands of feet of fossil-rich black shale, were laid down on top of the Dakota Sandstone.

Chapter 5: The Laramide Orogeny

As the Cretaceous seaway was beginning to recede about 70 million years ago, the first stirrings of the episode of mountain building that laid the foundations of the Front Range and most of the other major Colorado ranges began. Plate movements along the western edge of the continent began to buckle the Earth's crust, raising domes and elongate welts of basement rocks and their sedimentary cover. Many of the uplifts were bounded by folds or by faults along which slabs of rock were uplifted and moved several miles with respect to the rocks beneath them. This episode of mountain building is called the Laramide orogeny.

The Golden fault, which marks the eastern boundary for the Front Range in Jefferson County, is one of the major Laramide range-bounding faults. Along it basement rocks of the range have been uplifted and carried several miles eastward, while the once-horizontal beds of sedimentary rocks beneath the overriding block bent upward so that they generally slope eastward. The Golden fault is commonly portrayed on maps and diagrams as a single west-sloping fault, but in reality it is probably a complex zone of many interlaced faults of various orientations. The Laramide orogeny ended about 50 million years ago. During the orogeny, movement along the Golden fault and other Laramide folds and faults raised the basement rocks in the highest parts of the range by as much as 20,000 or 25,000 feet relative to the basement rocks beneath Denver and the surrounding plains. While this may seem like an enormous amount of uplift, spread over the 20 million years or so that the orogeny was active, the average rate of uplift would have been less than a hundredth of an inch per year. However, the uplift probably occurred in a series of discrete episodes at different times in different parts of the range, so that the actual rates of uplift were probably much faster. The total uplift does <u>not</u> mean that the Front Range peaks were ever 25,000 feet high! The height of a mountain at any given time is determined by the balance between the rate the rocks that form it are uplifted and the rate at which they are being eroded. Thus the Laramide Front Range may never have been higher or more rugged than the range we see today.

Most episodes of mountain building are accompanied by the emplacement of widespread bodies of igneous rocks, but the Laramide orogeny is an exception. The only igneous rocks that date from the Laramide orogeny in Jefferson County are small intrusive bodies of potassium-rich basalt near the mountain front north of Golden, and the lava flows that cap North and South Table Mountains, which were probably fed from the intrusive bodies. However, a number of bodies of fine-grained light-colored rocks with the approximate composition of granite intrude the Precambrian basement rocks between Breckenridge and Boulder. These bodies are part of a northeast-trending belt of similar intrusions of Laramide and younger age that extends from the San Juan Mountains to the Front Range near Boulder. This belt, known as the Colorado mineral belt, hosts almost all of the world class deposits of gold, silver, lead, and zinc for which Colorado is famous, including those at Silver Plume, Georgetown, Idaho Springs, Central City, and Black Hawk.

Chapter 6: Destruction of the Laramide Mountains

Erosion attacked the Laramide uplifts as soon as they began to rise and continued after uplift ended. By the latter part of the Eocene epoch (roughly 45 to 35 million years ago), most of the Laramide Front Range uplift was reduced to a relatively flat landscape with scattered rounded hills and occasional low mountains separated by broad shallow valleys. If you look west from the flatlands around Denver you will see that broad areas in the easternmost foothills of the Front Range consist of flat-topped ridges, all of which stand at about the same level---the flat top of Lookout Mountain is a good example. These flat ridge tops are parts of the post-Laramide landscape, which is commonly referred to as the Rocky Mountain erosion surface.

At least 9000 feet of sedimentary rocks and an unknown but significant amount of basement rocks were stripped from the rising Front Range during and after the uplift. Some of the debris was shed westward into South, Middle, and North Parks, but the great bulk of the eroded material was transported eastward, filling an extensive basin just east of the range to depths of several thousand feet and depositing an eastward-tapering blanket of sediments, chiefly shale, sandstone, and conglomerate, for 50 miles or more to the east. The lava flows that cap the Table Mountains were erupted about 64 million years ago, while these sediments were being deposited, and were buried beneath younger strata as the sediments continued to accumulate. Along the mountain front the upper surface of this sedimentary apron was at approximately the same level as the as Rocky Mountain erosion surface.

Chapter 7: Shaping the Modern Landscape

The landscape we see today was carved from the post-Laramide landscape during a period of erosion that began about 26 million years ago, during the later part of the Oligocene epoch. The cause of this erosional episode is still a matter of debate. Many geologists believe that erosion was accelerated by uplift of the entire Rocky Mountain region by deep-seated forces within the Earth's mantle. However, it has recently been argued that uplift was minor and that the increased erosion was the result of climate change from the relatively warm and dry climate of the Eocene to a cooler wetter climate with increased stream flows in the Oligocene. Probably both uplift and climate change contributed to the intensified erosion.

Whatever the cause, streams began to dissect the post-Laramide landscape, cutting deep canyons in the ancient basement rocks, accenting the peaks, and beginning to remove the apron of sediment along the mountain front. Apparently erosion was not continuous, but took place in a series of spurts separated by intervals of relative stability. By sometime in the Miocene, between about 23 and 5 million years ago, a distant ancestor of Clear Creek had carved a V-shaped canyon into the Rocky Mountain erosion surface to depths of several hundred feet. This early canyon was later filled with deposits of gravel containing huge boulders. As erosion continued the creek abandoned its old canyon and shifted to its present course and began to cut the modern canyon, leaving the erosion-resistant gravel in the old stream course as isolated deposits capping ridges as much as 800 feet above the present stream. During this early phase of canyon cutting, Clear Creek and other Front Range streams spread another thin but more extensive sheet of sediment, chiefly clay, sand, and gravel, across the older Laramide sedimentary apron eastward on to the plains. This deposit forms the famous Ogallala aquifer, which provides ground water to extensive areas in the High Plains.

At the time the Ogallala gravel apron was being deposited, the South Platte River had not yet excavated the broad valley in which central Denver is located, and Clear Creek was flowing on sedimentary rocks of the old Laramide apron, more than 700 feet above its present level, above the level of the top of the Table Mountains lava flows.

As erosion continued, the South Platte River established its present north-trending course through Denver and began to deepen its valley. Streams flowing out of the mountain canyons to join the South Platte were forced to deepen their valleys through the soft sedimentary rocks east of the mountain front to keep pace with the down-cutting of the main river. The behavior of the flatland streams seems to have been controlled by climate changes. During times of wet and moist climate, the streams were larger and more powerful and cut deep narrow valleys. When the climate became hotter and dryer, flow was greatly reduced, as was the ability of the streams to carry sediment. Because their channels were choked with coarse gravel carried in during the earlier more powerful stream flows the streams tended to cut laterally into the soft Cretaceous and Tertiary sedimentary rocks in their banks. Ultimately this produced a gently eastward sloping flat surface mantled with a thin layer of sand and gravel. Surfaces of this kind are called pediments and they are common in areas of desert or semi-desert climates throughout the world. At least four pediments have been recognized along the eastern foot of the Front Range. Only a few scattered remnants of the highest pediment are preserved. They form small gravel-topped hills and benches that stand as much as 800 feet above most major streams at the mountain front. This pediment probably formed about 3 million years ago. A much more conspicuous pediment forms Rocky Flats. Its gravel covered surface stands about 750 feet above the major adjacent streams and it probably formed about 1.5 million years ago. Remnants of this same surface are found also in the area of Roxborough State Park, about 15 miles south of Rocky Flats. The gravel at both Rocky Flats and Roxborough Park rests on the edges of the Paleozoic and Mesozoic strata that were upturned during the Laramide orogeny, suggesting that the hogbacks along the mountain front were shaped by erosion after the Rocky Flats pediment had been formed. Indeed, the more or less level tops of the hogbacks may mark the level of the Rocky Flats surface even where the surface itself has been removed by erosion. Two more lower and more extensively preserved pediments have also been recognized. They must have been cut after the Hogbacks were formed. Sediments that cover the uppermost contain a thick layer of volcanic ash which was erupted from one of the volcanic centers near Yellowstone 640,000 years ago. The lower surface probably formed about 240,000 years ago. Since that time streams have continued to cut down through the pediments to create the valleys we see today.

The present relief at the mountain front, about 2,000 feet between Golden and the Lookout Mountain Nature Center, is entirely due to erosion of the soft sedimentary rocks of the post-Laramide debris apron. Green Mountain and the Table Mountains are remnants of the eroded apron that were protected from erosion by resistant caps. Green Mountain is capped by thick layers of erosion resistant conglomerate; the Table Mountains are capped by thick flows of hard basalt.

Chapter 8: The Ice Ages

Most of the erosion of the uplifted roots of the Laramide mountains was the work of rock weathering and removal of material by streams and rivers. In the last 2 million years, however, glaciers played a major role in shaping the mountain landscape. Although there were several earlier periods of glaciation in the Colorado mountains, the principal glacial advances that shaped the present mountain landscape were the Bull Lake glaciation between about 170,000 and 120,000 years ago, and the Pinedale glaciation between about 30,000 and 12,000 years ago.

None of the Bull Lake or Pinedale glaciers in the Front Range advanced far enough to reach the eastern front of the mountains. The nearest moraines marking the maximum advance of the glaciers are along Clear Creek near Empire Junction, about 25 miles upstream from the mountain front. Nevertheless, glaciations had significant effects on the landscape development and ecology of the areas east of the glacial limits. Even when a glacier is stable or advancing, huge volumes of melt water pour from its snout. The water flow is greatly enhanced if the climate warms and the glacier retreats. The torrential flows of melt water carried enormous amounts of gravel from the bed of the glacier and from rocks trapped in or carried on the surface of the melting ice. These melt water floods deposited low terraces along the major stream valleys that by this time had cut 80 feet or more below the level of the lowest pediment surfaces. Most of downtown Denver is built on the terrace formed by outwash deposited during the Pinedale glaciation; the same outwash terrace can be recognized for many miles along the South Platte River downstream. The glacial outwash terraces in and around Denver contain fossils of animals that inhabited the area during the Ice Ages, including mammoths, mastodons, grizzly bears, bison, deer, and great ground sloths.

During the peaks of the glaciations, high winds blowing across the bare floodplains of the streams raised clouds of sand and wind-blown silt (loess) and deposited their loads as widespread blankets across the adjacent pediments.

Studies of fossil beetles in one of the terraces near Denver suggest that 14,500 years ago, during the late stages of the Pinedale glaciation, mean July temperatures were about 6^{o} F lower and mean January temperatures were as much as 17^{o} lower than they are today. It has been estimated that vegetation zones in the Rocky Mountains were as much as 3,000 feet lower than they are today. If so, timberline in the Front Range would have been at about 8000 feet, and peaks like Centennial Cone, Genesee Mountain, and Bergen Peak would have been in the alpine zone, and the Lookout Mountain Nature Center would have been high in the montane zone. It seems likely that many ecosystems are still adjusting to changes in temperature and precipitation since the Pinedale.

Chapter 9: The Long View

The main conclusion we reach from looking at geology and geologic history is that landscapes and climates are constantly changing and that flora, fauna and ecosystems must be constantly adjusting to these changes. Recognizing and studying these natural changes is, or should be, one of the most exciting challenges to biologists and ecologists. Every time we hear of a home damaged by swelling clay, a rockfall closing the highway in Clear Creek Canyon, or a Big Thompson flood we are reminded that geologic processes are still at work, and that the landscape we see today is only one brief frame in a film that started billions of years ago and the end of which we will never know.

THE DARK BACKWARD ABYSM OF TIME
(The Tempest, act 1, scene 2)

Geology is all about time, and lots of it. Geologists spend their careers grappling with Shakespear's "dark backward abysm of time," and in order to understand our geologic story, it's necessary to have some concept of the length of geologic time, how it is divided, and how it is measured.

Geologists recognized as early as the late 17th century that it was possible to determine the relative ages of rocks using some simple rules. For example, in an undisturbed stack of sedimentary beds, each bed is younger than the bed below it. If a body of intrusive igneous rocks cuts across sedimentary beds, the intrusive rock must be younger than the rock it cuts. Conversely, if a sedimentary rock contains pebbles of some other rock, it must be younger than the rock which forms the pebbles.

In the early 19th century, geologists realized that sedimentary rocks could be classified by the fossils that they contain, and that fossils could be used to recognize rocks of the same age in widely separated regions (see "The Map that Changed the World " *by Simon Winchester). This ultimately led to the establishment of the geologic time scale in which time is divided into Eras, Periods, and Stages on the basis of the assemblages of fossils they contain. Many of the original names for these time intervals are still in use today.*

Although the geologic time scale has been used and refined for almost two centuries, it has one major fault: it does not tell us the length of geologic time or the time spans represented by various units it contains. There were many estimates of the age of the Earth based on such things as estimates of the rate of accumulation of sediments or the rate of accumulation of salt in the ocean. Perhaps the most famous was Lord Kelvin's estimate of about 50 million years based on his calculation of how long it would take a sphere of molten iron the size of the Earth to cool to its present temperature. It turns out that the greatest physicist of his day was off by three orders of magnitude,that is, about four billion years!

The reason for Kelvin's miscalculation is that he had no knowledge of radioactivity and the heat that it produces. The discovery of radioactivity in 1896 both invalidated Kelvin's calculations, and provided a way of measuring the absolute ages of rocks and minerals. The first attempts at absolute dating using decay of radioactive elements appeared in 1906, but it was not until the 1960's that absolute radiometric dating was refined and widely used. Radiometric dating cannot be used for sedimentary rocks, because it would only produce the age of the materials that were eroded to produce the sediment, but it can be applied to igneous rocks and to a certain extent to metamorphic rocks. However, ages of sedimentary rocks can be inferred by dating layers of volcanic ash (formed from igneous rocks) that were deposited with the sediments, or bracketed by dating igneous rocks that are known to be older or younger than the sediments based on the rules of thumb for relative ages.

Thus absolute radiometric dating has allowed us to determine both the age of the Earth, and to attach ages to the various divisions of the geologic time scale. In order to picture the relations between the geologic time scale and the absolute ages, it may be useful to use the "yardstick of geologic time" illustrated above. If we let a yardstick represent the length of time from origin of the Earth at one end and the present time at the other, the entire yardstick represents 4,540 million years (4.54 billion years) and each inch represents 125 million years. The length of time Homo sapiens *has inhabited the Earth is represented by the thickness of a thin sheet of paper at the top of the yardstick*

ROCKS AND MINERALS

Minerals are solid substances formed by natural processes that have a specific chemical composition (or range of compositions) and a characteristic crystal structure. Rocks are made up of mineral grains, generally of several different minerals, but in some cases, all of the same mineral. Rocks are classified by their mode of origin (sedimentary, igneous, metamorphic), by the minerals they contain, and by their texture (size, shape, and arrangement of the mineral grains). Geologists love to name things, and there are thousands of names proposed for various rocks, many of them redundant and most of them confusing. However, for the average visitor to Jefferson County Open Space Parks, knowing only a few general rock names is necessary:*

ROCK NAME	***PRINCIPLE MINERALS***	***TEXTURE AND OTHER FEATURES***
SEDIMENTARY ROCKS: Rocks made up of material carried by water, wind, or glacial ice and deposited on dry land or under water. Generally characterized by continuous layers (beds) fractions of an inch to hundreds of feet thick. May contain fossils.		
Sandstone	*Quartz, feldspar*	*Made of rounded or angular mineral sand grains ranging in size from BBs to grains of table salt cemented together by quartz, calcite, or clay. Color white, gray, yellow or red*
Shale	*Clay minerals*	*Individual mineral grains too small to distinguish with a hand lens. Breaks in thin slabs of chips. Color black, green, or red*
Limestone	*Calcite and/or dolomite*	*Individual grains too small to distinguish with a hand lens. Color generally light gray*
IGNEOUS ROCKS: rocks formed by cooling of liquid rock material (magma) either at depth (plutonic or intrusive rocks) or on the land surface (volcanic or extrusive rocks)		
Granite	*Quartz, feldspar, mica*	*Intrusive igneous rock made up of irregular interlocking grains of quartz, irregular to rectangular grains of white or pink feldspar, and scattered flakes of black or silvery mica. Grains range in size from fractions of an inch to an inch or so in diameter. Color gray, pink, or white. Technically the name granite is used for rock of a very specific mineral and chemical composition, but our purposes we apply it to any coarse grained light colored plutonic rock*
Pegmatite	*Quartz, feldspar, mica*	*Intrusive igneous rock closely related to granite, but consisting of mineral crystals several inches to several feet in diameter. Occurs as dikes and irregular bodies in granite or in surrounding metamorphic rocks. Formed at late stages in crystallization of granite magma where materials such as water, carbon dioxide and fluorine have been concentrated, slowing crystallization and allowing growth of very large crystals.*
"Basalt"	*Calcium-rich feldspar, pyroxene, and olivine*	*Dark gray or black lava composed principally of mineral grains that are too small to distinguish with a hand lens, but commonly containing scattered larger crystals of any or all of the major constituent minerals. Commonly contain ovoid cavities fractions of an inch to several inches in diameter left by gas bubbles in the cooling lava. The only basalt flows in Jefferson County are those that cap North and South Mountains. The Table Mountain flows are a special type of basalt called shoshonite, which contains more potassium than other basalts and, as a result, contains some potassium-rich feldspar, which is never found in normal basalts.*
Metamorphic rocks: rocks formed from sedimentary or igneous rocks by exposure to high temperature and/or pressure, which cause new minerals to form, and old minerals to recrystalize into larger grains. Generally textures and structures of the parent a rock are partially or completely destroyed and new textures to develop by alignment of mineral grains in streaks and planes segregation of various minerals into layers or discontinuous lenses.		
Gneiss (pronounced "nice")	*Quartz, feldspar, black and/or white mica,*	*White, light gray, or dark gray rock in which mineral grains or aggregates of grains are arranged in conspicuous streaks or in layers containing different proportions of the light-and dark-colored minerals. Mineral grains range in size from small fractions of an inch to several inches. Produced from metamorphism of sandstone, volcanic rocks, or granite. Generally breaks into irregular blocks.*
Amphibolite	*Hornblende, calcium-rich feldspar, little or no quartz*	*Dark green rock composed of needle-like crystals of green hornblende small fractions of an inch to as much as an inch in length, and irregular smaller crystals of white feldspar. Occurs as layers or pods a few inches to tens of feet thick in gneiss or schist. Produced by metamorphism of basalt or intrusive rocks of similar composition.*
Schist	*Mica, quartz, feldspar*	*Mica-rich rock in which mica flakes fractions of an inch to an inch or more in diameter are arranged in parallel planes giving the rock a silvery appearance and causing it to break into chips or large plates. Quartz and feldspar commonly form pods and layers parallel to the mica plates. Formed by metamorphism of shale*
Quartzite	*Principally quartz, but commonly with some feldspar or other minerals*	*Hard light gray or white rock in which quartz grains are firmly interlocked or cemented together by quartz or other minerals. Forms by metamorphism of sandstone. Occurs as layers in gneisses in a few areas, but forms a large body in the Open Space in Coal Creek Canyon, where it contains abundant pebbles of white quartz an inch or several inches in diameter*
Marble	*Calcite*	*Soft easily scratched white or light gray rock produced by metamorphism of limestone. Calcite grains generally small fractions of an inch in diameter Forms scattered lenses and layers in gneiss or schist, but is seldom seen in natural outcrops because it is so easily eroded.*

* For a description of the minerals mentioned in the table see the glossary or refer to one of the following books:

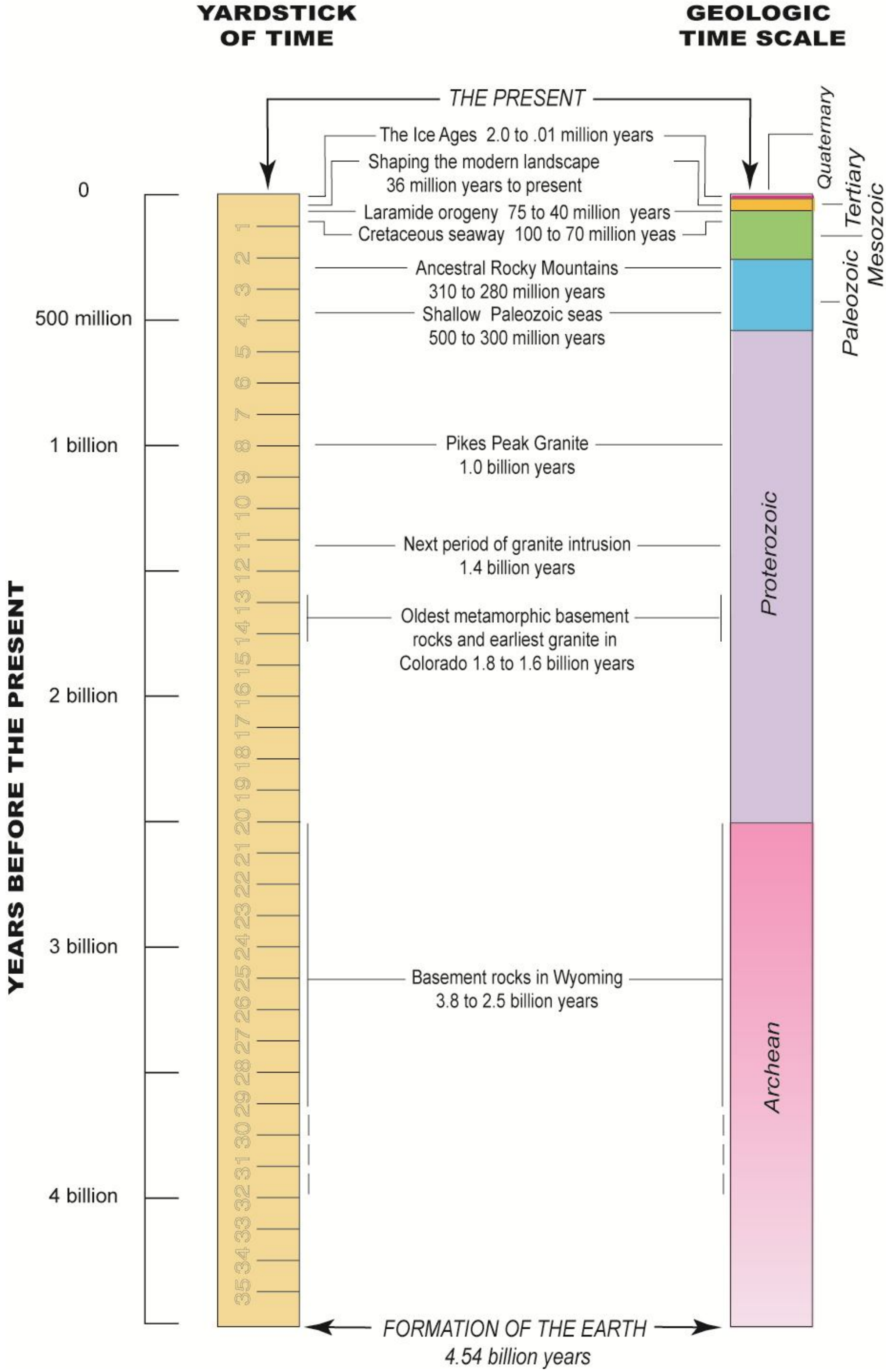
Smithsonian Handbooks: Rocks and Minerals by Chris Pellant

National Audubon Society Field Guide to North American Rocks and Minerals by C. W. Chesterman

Simon and Schuster's Guide to Rocks and Minerals by Martin Prinz, George Harlow, and Joseph Peters

GEOLOGIC OVERVIEW OF SELECTED OPEN SPACE PARKS

NAME	PRINCIPAL FEATURES	COMMENTS
PARKS LARGELY IN BASEMENT ROCK		
Centennial Cone	Layered gneiss of several types; pegmatites; high level Tertiary gravel; parts of post-Laramide erosion surface.	• Best bedrock outcrops are on slopes of Clear Creek Canyon.
White Ranch	Largely silvery mica schist; some amphibolites in northern part; conspicuous pegmatites: parts of post-Laramide erosion surface.	• Basement rocks less metamorphosed than elsewhere in the area. Bedding is preserved in many places. • Spectacular crystals of andalusite in some outcrops. • Layers of metamorphosed conglomerate, but none accessible to visitors. • Rocks here may be younger than those in other parts of the Front Range.
Alderfer/Three Sisters	Scenic pinnacles are coarse-grained 1.4 billion year old granite; surrounding areas are biotite schist containing many small pods and layers of granite. High-level gravel on flat-toped ridge northeast of Three Sisters.	• Granite weathering forms and soils. • Gravel similar to that above Clear Creek probably marks ancient course of Bear Creek.
Pine Valley Ranch	Entirely underlain by 1.0 billion-year-old Pikes Peak granite; high level gravel occurs on top of ridge just north of park.	• Granite weathering produces dry sandy soil on which wildfires are common • High level gravel marks former course of the North Fork • River erosion has formed conspicuous potholes in granite • About half of the flow in the river comes through the Roberts Tunnel from Dillon Reservoir.
Other parks in predominantly basement rocks include Mt. Galbraith, Windy Saddle, Apex, Mount Falcon, Lair o' the Bear, Mt, Lindo; Flying J Ranch, Meyer Ranch, Deer Creek Canyon; and Reynolds.		
PARKS ALONG THE MOUNTAIN FRONT AND HOGBACK		
Matthews/Winters	Sedimentary rocks deposited form the time of the Ancestral Rocky Mountains to early in the time of the Cretaceous Seaway. Includes famous exposures of at Dinosaur Ridge and the I-70 roadcut; scattered remnants uppermost pediments cut during erosion of post-Laramide sedimentary apron; gravel floored wind gap in hogback and landslide in Fountain Formation formed during the post-Laramide erosion.	• Time gap represented by unconformity between Fountain Formation and basement rocks represents about one quarter of the age of the Earth. • Dinosaur bones and tracks on Dinosaur Ridge visited by thousands of people each year. They are found in rocks deposited before and during the early stages of incursion of the Cretaceous Seaway. • Deep wells near Soda Lakes provide evidence of the tremendous uplift during the Laramide orogeny. • Wind gap in Hogback marks former course of Mount Vernon Creek. It provides a classic example of stream capture.
South Valley	Upturned sedimentary rocks along the Mountain Front. Post-Laramide pediment surfaces at several levels.	• Sedimentary layers are folded and are much more gently inclined than those farther north along the hogback. • Most prominent hogback in the park is formed by the Lyons Sandstone; the Dakota Sandstone forms a second hogback east of the park. The Fountain Formation underlies the valley between the Lyons hogback and the mountain front, but does not form conspicuous outcrops as it does farther north. The Lyons Sandstone was deposited in sand dunes in a desert environment. The sand grains are loosely cemented by calcium carbonate. This probably explains the intricately pitted and fluted rock faces which provide convenient nesting places for a variety of birds.
North and South Table Mountains	Both capped by lava flows that were erupted from vents that lie 2-3 miles to the northwest.	• Lava flows were erupted 63-64 million year s ago, during a pause in accumulation of the apron of sand and gravel shed from the rising Front Range during Laramide orogeny. • The flows poured southeast down a broad shallow valley; they were buried by younger sediments as uplift of the Front Range continued • Subsequent erosion has removed the sediments above them and the connection with their up-valley source. As erosion continued, Clear Creek cut through the once continuous flows and separated North and South Table Mountains. They stand as mountains because the hard lava has protected the underlying sand and gravel from erosion .
Other mountain front park: Hildebrand Ranch		
PIEDMONT PARKS		
Crown Hill	Located on pediment cut between about 410 and 475 thousand years ago during erosion of the post-Laramide sedimentary apron along the eastern flank of the Front Range.	• Underlain by wind-blown silt and sand swept from floodplains of nearby streams during the during the Bull Lake and/or Pinedale glaciations. Loess is 5-10 feet thick and is underlain by gravel which caps the surface of a pediment which is cut in shale, siltstone and sandstone. None of these deposits crop out within the park, but their presence and distribution is inferred from nearby outcrops. • Loess blanket offers easy digging for graves in adjacent cemetery.
Other piedmont parks: Van Bibber, Welchester Tree Grant		


YARDSTICK OF TIME
GEOLOGIC TIME SCALE
THE PRESENT
The Ice Ages 2.0 to .01 million years
Shaping the modern landscape 36 million years to present
Laramide orogeny 75 to 40 million years
Cretaceous seaway 100 to 70 million yeas
Ancestral Rocky Mountains 310 to 280 million years
Shallow Paleozoic seas 500 to 300 million years
Pikes Peak Granite 1.0 billion years
Next period of granite intrusion 1.4 billion years
Oldest metamorphic basement rocks and earliest granite in Colorado 1.8 to 1.6 billion years
Basement rocks in Wyoming 3.8 to 2.5 billion years
FORMATION OF THE EARTH 4.54 billion years
YEARS BEFORE THE PRESENT
0
500 million
1 billion
2 billion
3 billion
4 billion
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Quaternary
Tertiary
Mesozoic
Paleozoic
Proterozoic
Archean

THE GEOLOGIC TIME SCALE

(note that the size of the boxes does not represent the lengths of time that the various divisions represent)

Eon	Era	Period	Epoch	Age (million years)
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01
			Pleistocene	2.6
		Tertiary	Pliocene	5.3
			Miocene	23.0
			Oligocene	33.9
			Eocene	54.8
			Paleocene	65.5
	Mesozoic	Cretaceous	Late Cretaceous	99.6
			Early Cretaceous	144
		Jurassic		200
		Triassic		251
	Paleozoic	Permian		299
		Pennsylvanian		318
		Mississippian		359
		Devonian		416
		Silurian		444
		Ordovician		488
		Cambrian		542
Proterozoic	Late Proterozoic			900
	Middle Proterozoic			1,600
	Early Proterozoic			2,500
Archean	AGE OF THE EARTH			4,540

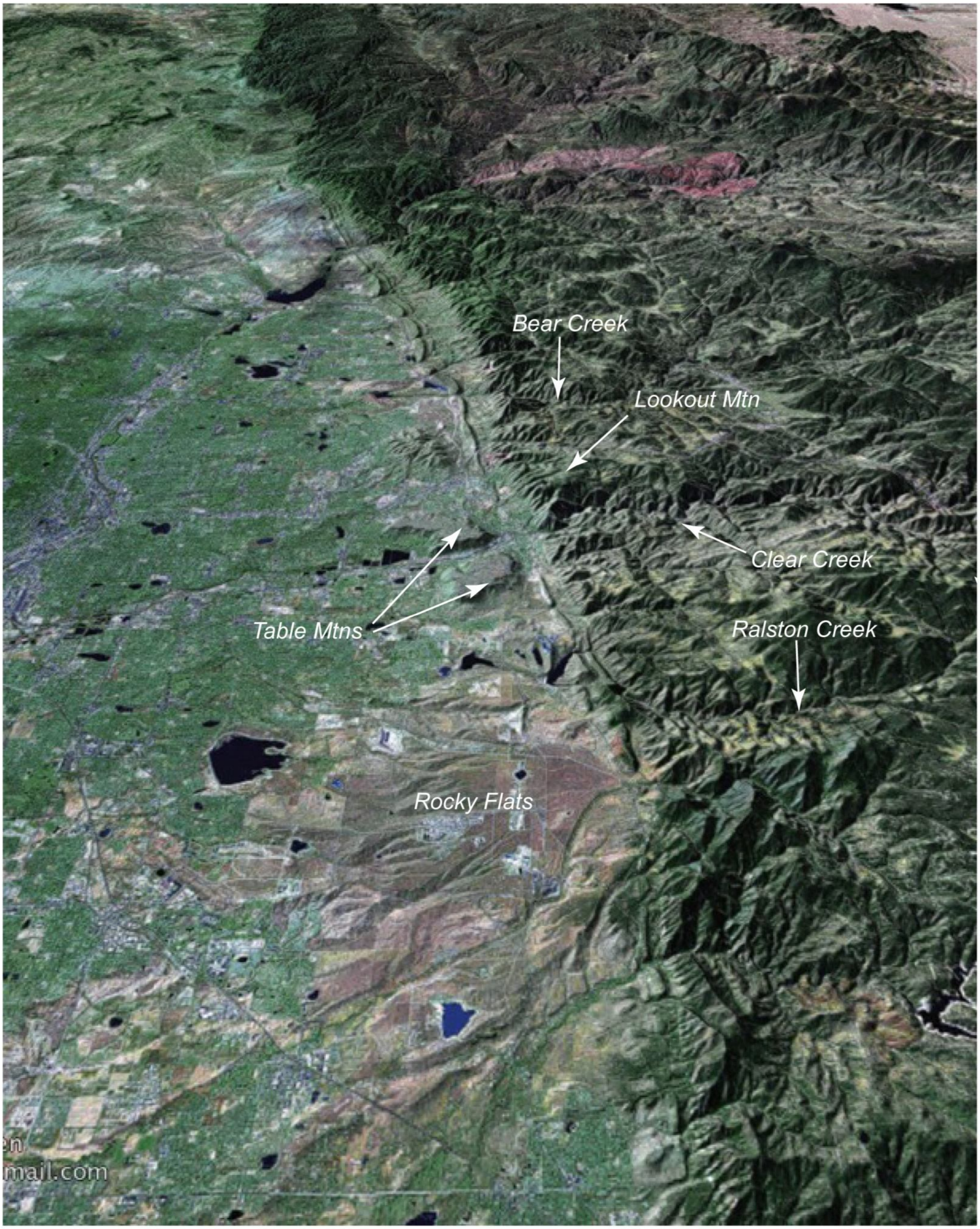


Figure 1. An astronaut's view of the eastern flank of the Front Range. View is south from over Rocky Flats. The rugged forested area on the right (west) is underlain by basement rocks, chiefly metamorphic rocks and granite; softer flat-lying sedimentary rocks underlie the flatlands to the left (east). The discontinuous hogbacks along the mountain front are formed by east-sloping layers of sedimentary rocks turned up during uplift of the Front Range. (Picture by William Bowen, California Geographical Survey, available at http://geodata.csun.edu).

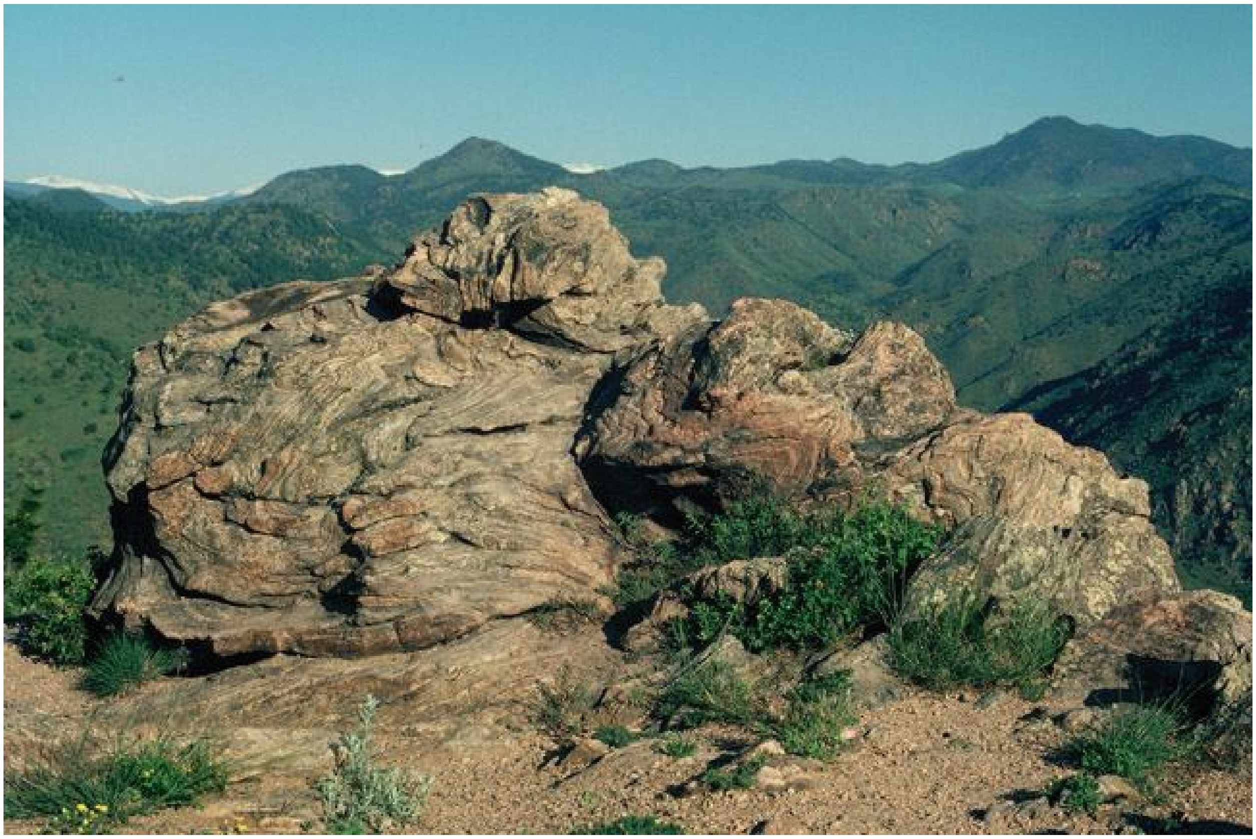


Figure 2 A. Contorted 1.7 billion year old metamorphic rocks along the Beaver Brook Trail west of the Lookout Mountain Nature Center.

Figure 2 B. Typical outcrop of 1.4 billion year old granite in Alderfer/Three Sisters Park

Figure 3. Outcrops of the Fountain Formation in Red Rocks Park. Rock is chiefly red feldspar-rich sandstone containing thin layers of conglomerate deposited during the erosion of the rising Ancestral Rocky Mountains. These beds were originally nearly horizontal but were tilted during later uplift of the Front Range during the Laramide orogeny. Inset shows close up of typical sandstone with a thin layer of conglomerate. Pebbles in the conglomerate are chiefly quartz, but some are pieces of basement rocks. The red color of the sandstone is caused by iron oxide (essentially rust), which coats the mineral grains.

Figure 4. The great unconformity at Red Rocks Park. Dotted line marks the contact between the red sandstone of the Fountain Formation (above) and basement rocks, here chiefly gneiss(below). The contact is called an unconformity because it separates rocks of widely different ages and histories and therefore marks an important gap in the geologic record. In this case, the difference in age between Fountain Formation and the basement rocks is about 1400 million years---nearly one third of the age of the Earth! Layers in the sandstone above the unconformity slope about 30^{o} east; rude layering in the gneiss is near vertical and trends about east-west. The conspicuous downward bulge in the unconformity is a small stream channel cut into the gneiss as the sand was being deposited. The stake near the right side of the picture is about 3 feet high.

Figure 5. The Ancestral Rocky Mountains as they might have appeared about 300 million years ago. The forest was entirely made up of tree ferns---flowering plants had not yet evolved. The foot of the mountains lay close to sea level, but the amount of relief may have been as much as the modern mountains. (Painting from the Denver Museum of Nature and Science).

Figure 6. Some pages in the book of time. The south wall of the roadcut on Interstate Highway 70 where it cuts through the Dakota Hogback exposes colorful east-sloping layers of sedimentary rocks were upturned from a near-horizontal position during the Laramide orogeny. These layers are pages in the book of time that record of events spanning about 55 million years, beginning after the destruction of the Ancestral Rocky Mountains and extending to the incursion of the Cretaceous Seaway. However, as we shall see, more than half the pages are missing!

The oldest layers, the Morrison Formation, were deposited between 155 and 148 million years ago. Its green and red shale interlayered with beds of gray of yellow sandstones were deposited by streams that flowed eastward from highlands near the western edge of the continent. They were deposited in a semi-desert landscape watered by intermittent streams and shallow lakes flanked by sufficient vegetation to support a large variety of animals, including some of the largest dinosaurs that ever lived. Many of their bones were entombed in the Morrison rocks.

Deposition of the Lytle Formation, the lower (older) part of the Dakota Group, began about 110 ago, leaving a gap in the geologic record of about 30 million years. The Lytle is composed mostly of tan or gray sandstone and lenses with some layers of red and yellowish shale. The sandstone bodies were deposited in channels of large northeast-flowing rivers; the shale layers represent mud deposited on the floodplains between channels.

The Plainview Formation, the younger (upper) part of the Dakota Group records the first flooding by the waters of the Cretaceous Seaway. Earliest layers of sandstone and black shale contain casts of tree roots and burrows of worms and clams. They indicate deposition in tidal mud flats. The prominent white sandstone layer and the black shale directly below it were evidently deposited in a large tidal delta at the mouth of a major river. A thin layer of volcanic ash in beds equivalent to the top of the delta deposits along Alameda Parkway has been dated as about 105 million years on Dinosaur Ridge. The uppermost (youngest) layers of the Dakota Group are principally white sandstone deposited in beaches, barrier islands, sandbars, and tidal ponds; the thin layers of black shale were probably deposited in shallow bays and marshes inland from the barrier islands. One of these layers contains the famous dinosaur tracks on Dinosaur Ridge, and nearby layers contain mud cracks, animal burrows, and ripple marks. On the eastern side of the Hogback the Plainview Formation is overlain by black shale derived from thousands of feet of mud deposited in deeper waters of the seaway during the next 30 million years.

Figure 7. Dinosaur tracks on Dinosaur Ridge. The large three-toed tracks were made by a large plant-eating dinosaur, which commonly traveled in herds. The small tracks to the left may have been made by a juvenile. The tracks have been dusted with charcoal so that they are more easily visible. Circular depressions mark places where tracks were removed by vandals before the outcrop was protected by the Friends of Dinosaur Ridge

Figure 8. Ripple marks are formed in shallow tide pools where gentle winds ripple the water surface and cause small intertwining ridge of sand to form on the bottom. Left photo shows ripple marks in 100 million year old Dakota Sandstone on Dinosaur Ridge. Right hand photo shows ripple marks on a modern beach. Notice the human footprints.

Figure 9. Pterosaurs soar over the waters of the Cretaceous Seaway about 70 million years ago, while the mud that would become the thick blanket of black shale that now overlies the sandstones of the Dakota Group was being deposited. (Painting from the Denver Museum of Nature and Science).

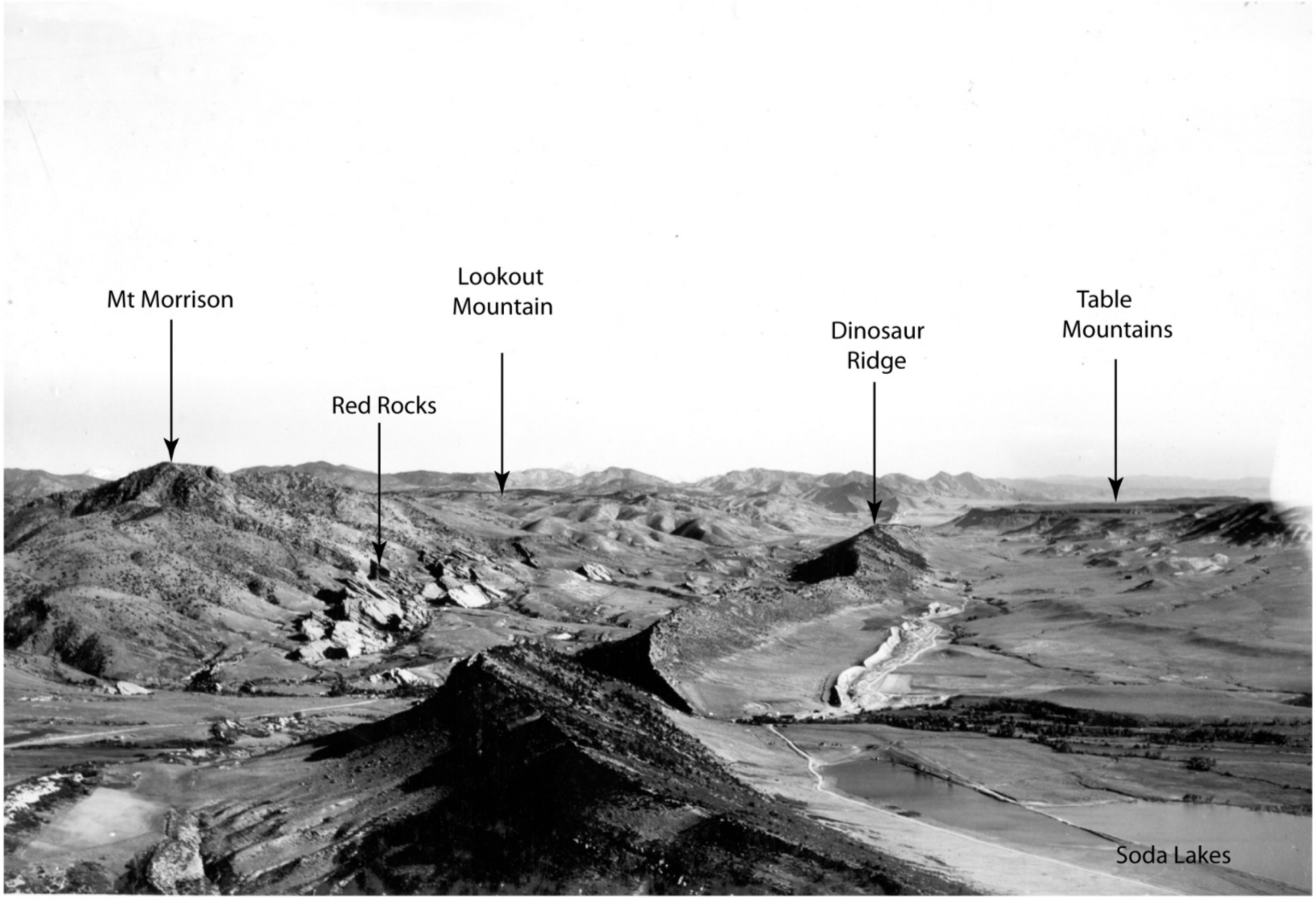


Figure 10. Upturned layers of sedimentary rocks along the mountain front photographed in 1938. View is north from approximately over the present location of U.S. Highway 285. The prominent hogback, which includes Dinosaur Ridge, is formed by sandstones of the Dakota Group. Smaller and less continuous hogbacks at Red Rocks are formed by red sandstones of the Fountain Formation. Small light-colored hogback east (right) of Dinosaur Ridge is formed by a bed of fossil-rich limestone interleaved with the black shale that overlies the Dakota Group: these exposures were largely destroyed during construction of C-470. The flat top of Lookout Mountains is a remnant of the Rocky Mountain erosion surface. Green Mountain lies just out of the picture to the right. (Photo by T.S. Lovering from U.S. Geological Survey Photo Library).

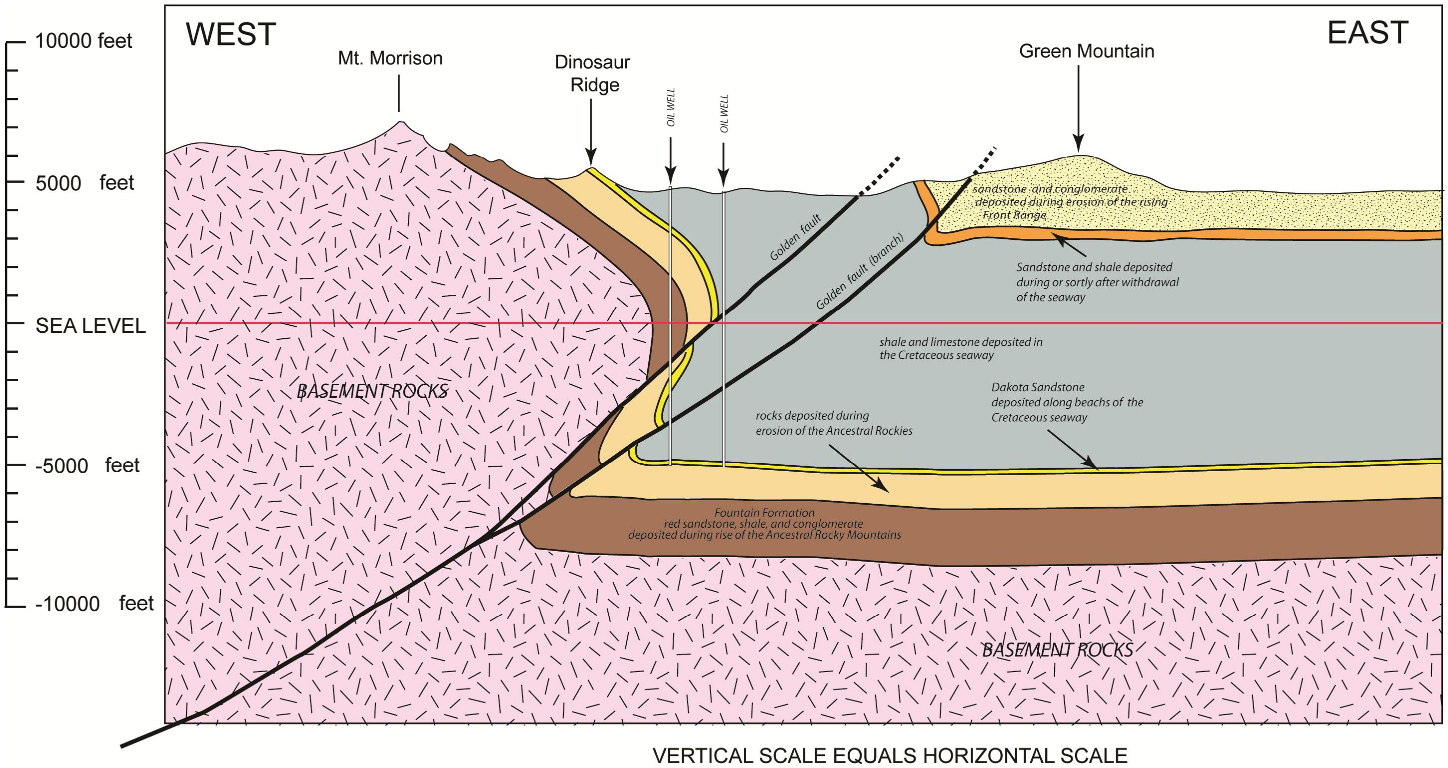


Figure 11. Cross section of the mountain front in the area pictured in fig. 10. The two oil wells shown in the section are immediately east of Soda Lakes. The Golden fault is depicted as a branching west sloping fault that carried rocks in the block west of the fault eastward over rocks east of the fault. Later interpretations suggest that the pattern of faults is much more complex, but the end result is the same in either case: basement rocks west of the fault have carried eastward for a mile or more, and the basement rocks at the top of Mt. Morrison have been uplifted by nearly 16,000 feet relative to the basement rocks to the east under the Soda Lakes.

Figure 12. View southeast from the top of Genesee Mountain. The level-topped ridges the stand at nearly the same level are remnants of the post-Laramide Rocky Mountain erosion surface. The surface has been deeply dissected by streams that have cut deep canyons during subsequent erosion. The mountains that rise above the surface in the right hand side of the picture were once low hills in the original surface.

Figure 13. Panorama of the Table Mountains from near Buffalo Bill's grave. The mountains are capped by lava that was erupted 63-64 million years ago and flowed southward down a shallow valley in the apron of sediments being shed from the Front Range. The flows were later buried as the sediments continued to accumulate, ultimately reaching the level of the Rocky Mountain erosion surface on Lookout Mountain. During subsequent erosion of the sediment apron above the lava flows were removed, but the flows protected the older sediments beneath them, leaving the flows standing as flat-topped mesas. As erosion continued Clear Creek gradually cut through the flows and deepened the valley that now separates North and South Table Mountains. It also destroyed the connection between the flows and their source, which lies several miles to the north.

Figure 14 A. Outcrop of coarse sandstone with discontinuous layers of conglomerate beneath the lava flows on North Table Mountain. These sedimentary rocks are part of the apron of sediments shed eastward from the rising Front Range during the Laramide orogeny. Pebbles are mostly quartz, but some are from basement rocks and from volcanic rocks that once covered much of the Front Range.

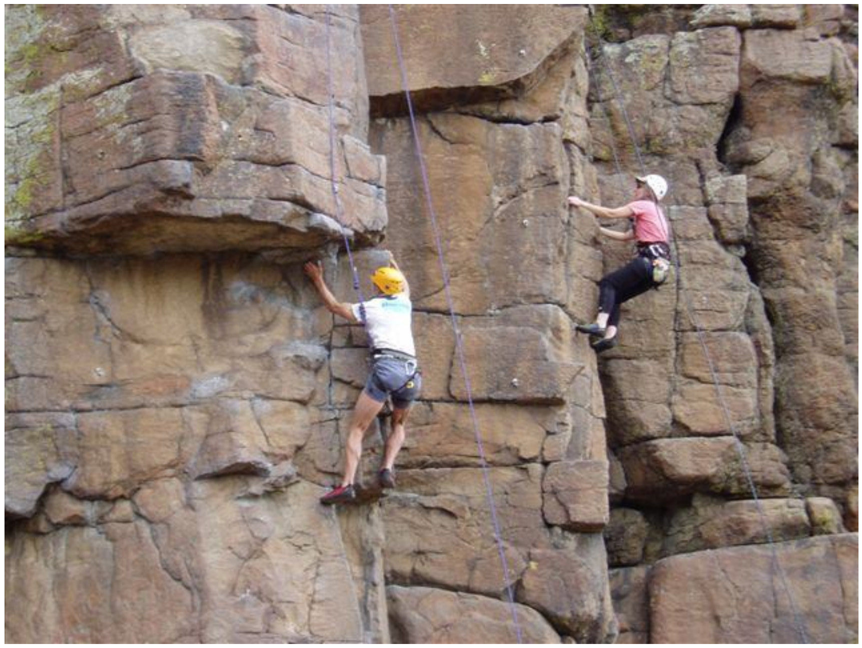


Figure 14 B. Climbing is extremely popular on the lava cliffs in the Golden City Park on the southwestern corner of North Table Mountain. The lava is divided into columns by vertical joints that formed as it cooled and contracted slightly. These vertical joints are being used as handholds by the climber on the right. The climber on the left is making use of nearly horizontal joints that formed across the columns, approximately parallel to the surface of the flow. This type of jointing, called columnar jointing, is characteristic of many lava flows; spectacular examples are the Giants Causeway in Ireland and the Devils Post Pile in California. It is clearly visible in almost all of the lava cliffs on the Table Mountains.

Figure 14 C. Close-up view of Table Mountain lava. The bulk of the rock is made of microscopic crystals of calcium- and sodium-rich feldspar, pyroxene, potassium-rich feldspar, olivine, and small amounts of black mica. This very fine-grained “groundmass” is studded with much larger crystals of feldspar, pyroxene, olivine, and magnetite. The rock, called shoshonite, differs from basalt in that contains appreciable amounts of potassium-rich feldspar (basalt contains none) and is gray or light pink (most basalt is dark gray or nearly black). In this picture the shiny crystals that glitter in the sun are feldspar, the black crystals are pyroxene or olivine, and the small white specs are gas bubbles that are filled white minerals called zeolites, which are a great interest to mineral collectors.

Figure 15. View of Clear Creek Canyon from near Windy Saddle. Arrows marked “g” point to ridges capped by high level gravels deposited by an ancestor of Clear Creek before the present canyon was cut. The arrow marked “rmes” points to a flat section of the Rocky Mountain erosion surface.

Figure 16. High level gravel of ancestral Clear Creek exposed along the Central City Parkway. This is the one of the very rare exposures of the gravel---in most places its extent can only be inferred by tracing out areas were abundant pebble and boulders occur on the land surface. In places the gravel is several hundred feet thick and apparently fills a narrow steep-walled valley cut into the Rocky Mountain erosion surface. The gravel contains no fossils or other material that can be dated, but is probably the same age as the Ogallala Formation in the High Plains, which is dated as between 10 and 2 million years. The large boulder just above the guard rail is about 5 feet long.

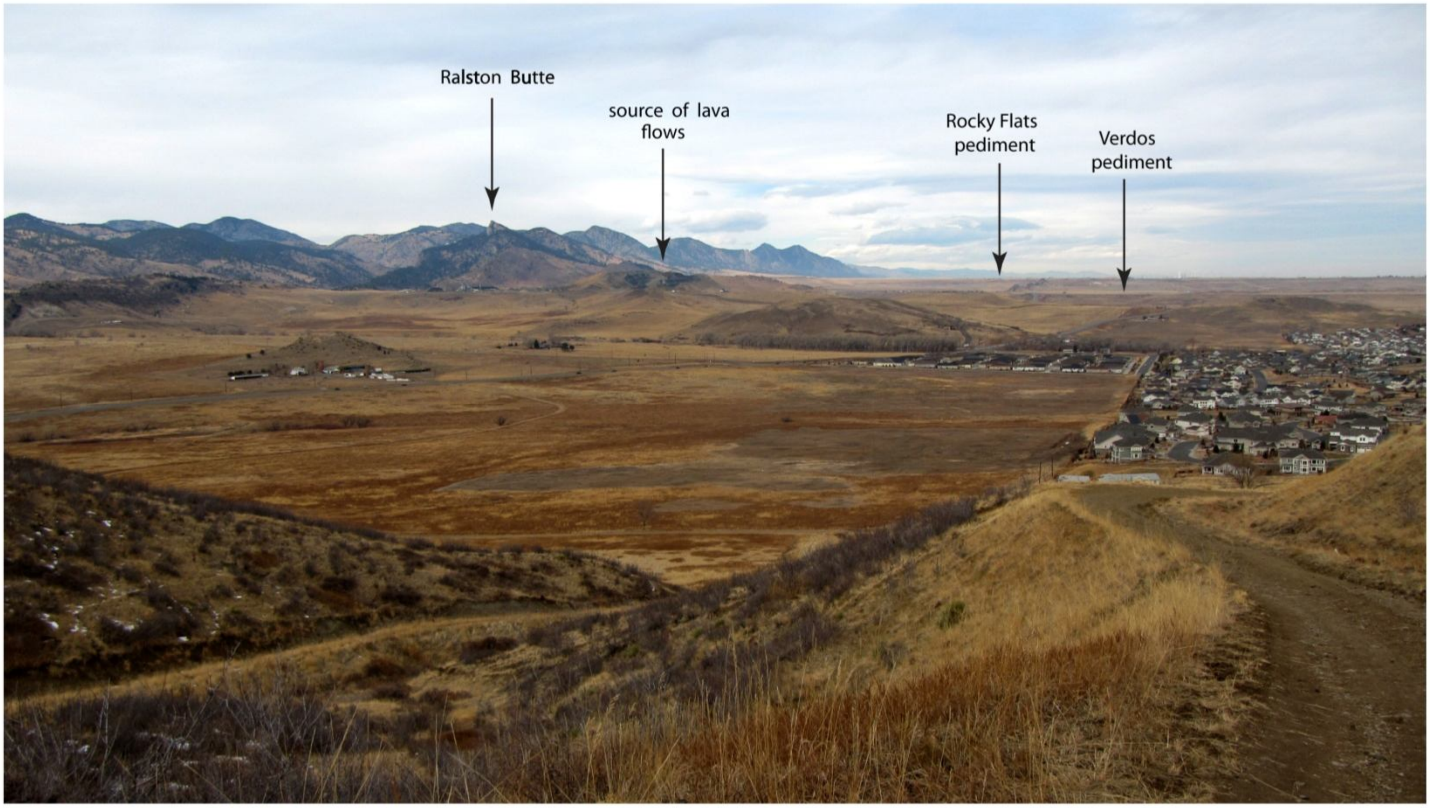


Figure 17 A. View north from North Table Mountain showing the Rocky Flats and Verdos pediments, and the location of the body of intrusive rock that fed the lava flows on the Table Mountains. Age of the gravel on the Rocky Flats pediment is estimated to be 1.0 to 1.8 million years old; gravel on the Verdos pediment contains a layer of volcanic ash dated as 640,000 years old.

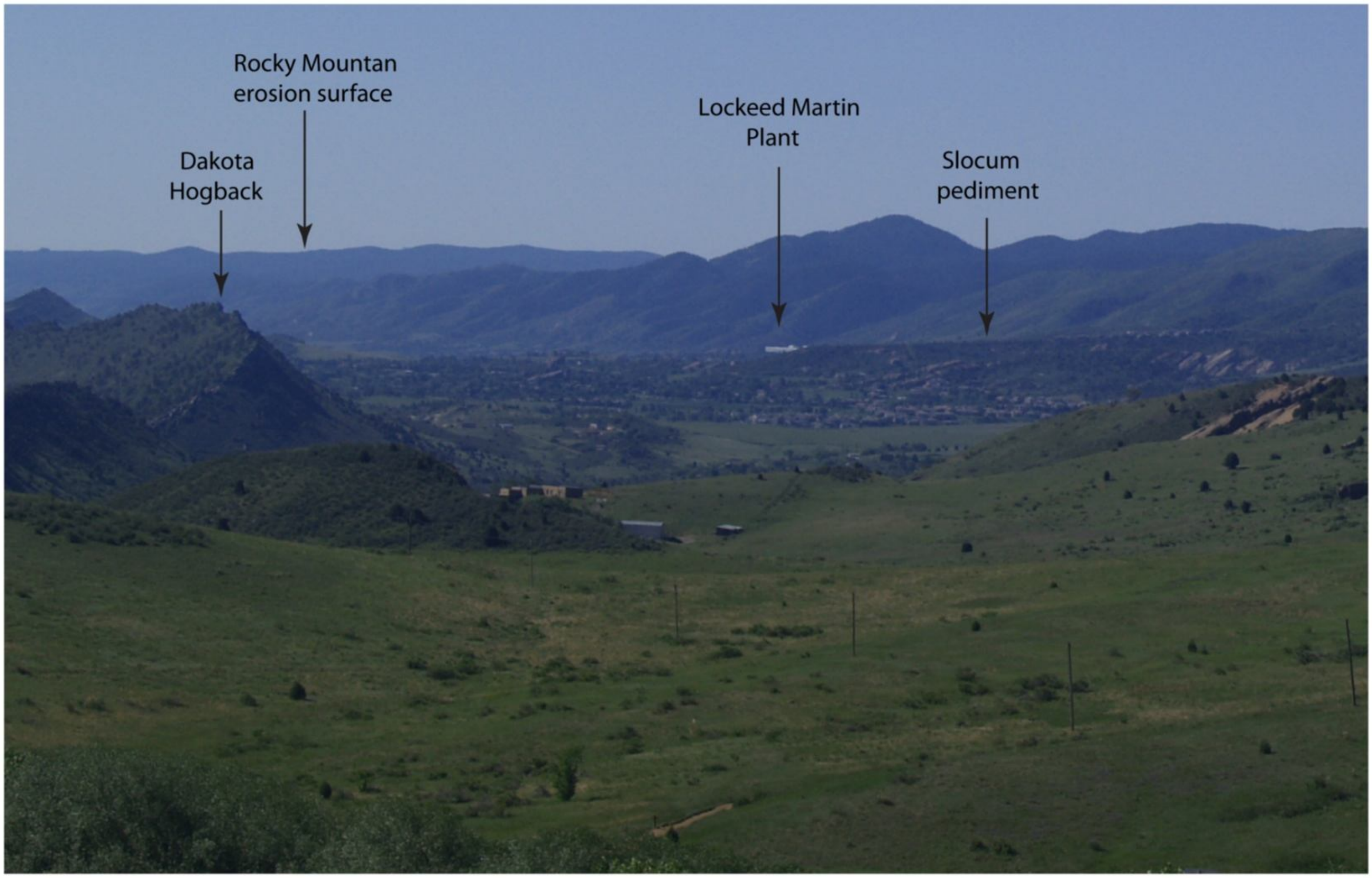


Figure 17 B. View south from I-70 at the mouth of Mt. Vernon Canyon showing the Rocky Mountain erosion surface on the skyline and the Slocum pediment near South Valley Park. Gravel on the Slocum pediment is about 240,000 years old.

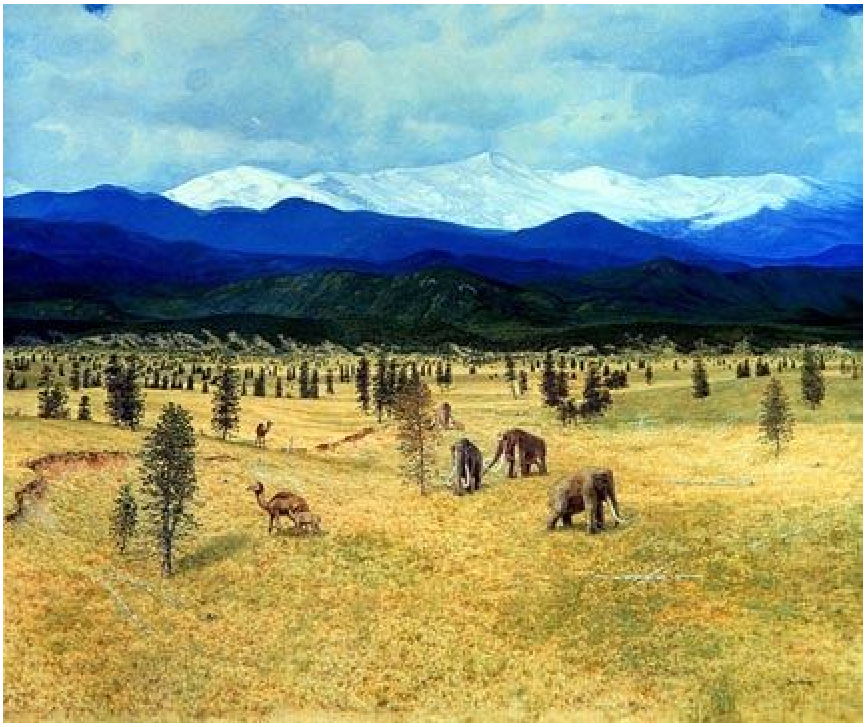


Figure 18. A summer day at Highlands Ranch about 16,000 years ago, during the last Ice Age. Mammoths and camels are grazing on prairie grass among the pine trees. (Painting from the Denver Museum of Nature and Science).

Figure 19 A. Damage from the Big Thompson Flood of July 31, 1976 that killed 144 people. Floods like this can occur in any of the major Front Range canyons.

Figure 19 B. Rockfall in Clear Creek Canyon. This rockfall took place on June 21, 2005. No one was killed or seriously injured, but two tractor-trailers were destroyed and U.S. Highway 6 was closed for 83 days.