Rocky Mountain

National Park Service
U.S. Department of Interior
Rocky Mountain National Park

Geology
Teacher Guide

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Rocky Mountain National Park

Rocky Mountain National Park (RMNP) is defined by the rugged Rocky Mountains that cut through the heart of the park from north to south. These mountains have shaped the landscape and created the conditions for the ecosystems we find within the park. Three of the park's ecosystems, the montane, subalpine, and alpine tundra are delineated by elevation, with the montane ecosystem comprising the lowest elevations in the park (5,600 – 9,500 ft.) and the alpine tundra ecosystem comprising the highest elevations in the park (11,000 – 14,259 ft.). This fragile alpine tundra, which comprises 1/3 of the park, is one of the main scenic and scientific features for which the park was established and is one of the largest and best preserved examples of this ecosystem in the lower 48 states.

Environmental Education was formalized at RMNP with the inception of the Heart of the Rockies program in 1992. Our curriculum is built on the principles of RMNP's founding father, Enos Mills. Mills felt children should be given the opportunity to explore and learn in the outdoors for nature is the world's greatest teacher. A belief that is kept alive today through every education program.

RMNP was established on January 26, 1915 through the efforts of local residents, especially Enos Mills, Abner Spague, and F.O. Stanley. Today the park covers 415 square miles of beautiful terrain, most of which is designated Wilderness.

Lessons Written and Compiled By
Rocky Mountain National Park Environmental Education Staff

Teacher Guide Created by Kellyn Griffin 2012; Updated by Meredith Dennis 05/2014;

Teacher Guides

Teacher guides have been developed by the education staff at RMNP and each focuses on a topic of significance to the Park. These guides serve as an introductory resource to the topic and the information provided is used by park educators to develop curriculum based education programs. Guides benefit teachers by providing the background information necessary to build a strong foundation for teaching students about specific park related topics; they may also be used as a resource for preparing students for field trips to RMNP. Each guide contains a resources and references section to provide for more in-depth study.

Rocky Mountain National Park
Education Program Goals

1. Increase accessibility to Rocky Mountain National Park for students from our gateway communities and under-served students who otherwise would not have the opportunity to visit the park.

2. Develop a variety of internal and external partnerships with other park operations, school districts, universities, professional educational organizations, agencies, friends groups, and various funding organizations.

3. Conduct workshops to train teachers to take a larger role in their student's experience at Rocky Mountain National Park.

4. Develop distance learning opportunities to serve students from outside our visiting area.

Schedule an Education Program with a Ranger

Field trips to national parks offer unique opportunities for studying and experiencing natural and cultural resources. Field trips are a great way to make abstract concepts from the classroom concrete. RMNP is an ideal outdoor classroom. It has a diversity of natural resources, easy spring and fall access, and is in close proximity to Front Range and Grand County communities.

Rocky Mountain National Park, like many national parks, offers ranger-led education programs. Heart of the Rockies, Rocky's education program, provides free field and classroom based education programs, aligned to Colorado education standards. School groups should make reservations at least 6 months in advance. National Park entrance fee waivers may also be available for school visits. For further information or to schedule a program please contact the Education Program Manager, at (970) 586-1338.

A variety of ranger-led education programs are offered seasonally. Programs in the spring and fall are generally similar focusing on a variety of park topics; programs in the winter are limited to snowshoeing programs and classroom programs focusing on winter. To see a list of the latest available programs please visit http://www.nps.gov/romo/forteachers/planafieldtrip.htm.

Geology
Background Information

Introduction

Rocky Mountain National Park is a unique and beautiful place. The park is made up of several geologic processes working together for billions of years creating the dynamic beauty you see today. This teacher guide is intended to give an overview of all the geologic history with details to the key events of Rocky Mountain National. The goal is to use this teacher guide as a resource to the geology of Rocky Mountain National Park and take the information back to the classroom, or better yet, in the field at Rocky Mountain National Park.

This geology teacher guide of Rocky Mountain National Park includes the geologic history starting 1.7 billion years ago and details key geologic events that have profoundly shaped the park. The geologic history of Rocky Mountain National Park includes several of examples of mountain building, inland sea advancement, erosion, and glaciers. In the teacher guide you will discover why the crystalline basement rock is so important to the stability of the Rocky Mountains, how glaciers have shaped the Continental Divide alpine and everything in between. Geology is the backbone to the climate and ecosystems of Rocky Mountain National Park and without all the geologic history Rocky Mountain National Park would not be what it is today.

In the teacher guide there are lessons to be used both in the classroom and on-site at Rocky Mountain National Park. It is important to remember when visiting Rocky Mountain National Park the high elevation dehydrates you quicker, gives you more exposure to UV rays and causes the weather to change quickly. Remember to come prepared and bring lots of water, sun screen, and plan accordingly for the weather. Beyond the geology of Rocky Mountain National Park, the park is also a great place to see diverse wildlife, colorful flowers and the experience of being on top of the world high in the alpine tundra. Regardless if you are visiting Rocky Mountain National Park for an educational experience or personal pleasure, always remember to follow park rules, leave no trace and be respectful to the wildlife and other visitors enjoying the park.

Geographic Setting of Rocky Mountain National Park

Rocky Mountain National Park is part of the Colorado Front Range. The Front Range rises west of Boulder, Denver and Colorado Springs and is the easternmost mountain range of the southern Rockies. The Rocky Mountains run from northern New Mexico with a northwest trend to British Columbia, Canada as part of the Continental Divide of North America. Throughout the Rocky Mountains there are 53 peaks that exceed 14,000 feet in Colorado and Longs Peak is the only "fourteener" within Rocky Mountain National Park. In Rocky Mountain National Park you find a range of geologic evidence that includes erosion, inland sea, mountain building and glaciations. The climate and ecosystems of Rocky Mountain National Park are a direct outcome from the geology. The altitude of the Continental Divide creates a rain shadow effect for the eastern side of Rocky Mountain National Park and the change of elevation with in the park allows for four different ecosystems to thrive. All aspects of Rocky Mountain National Park are a result of the geology that has sculpted the park today.

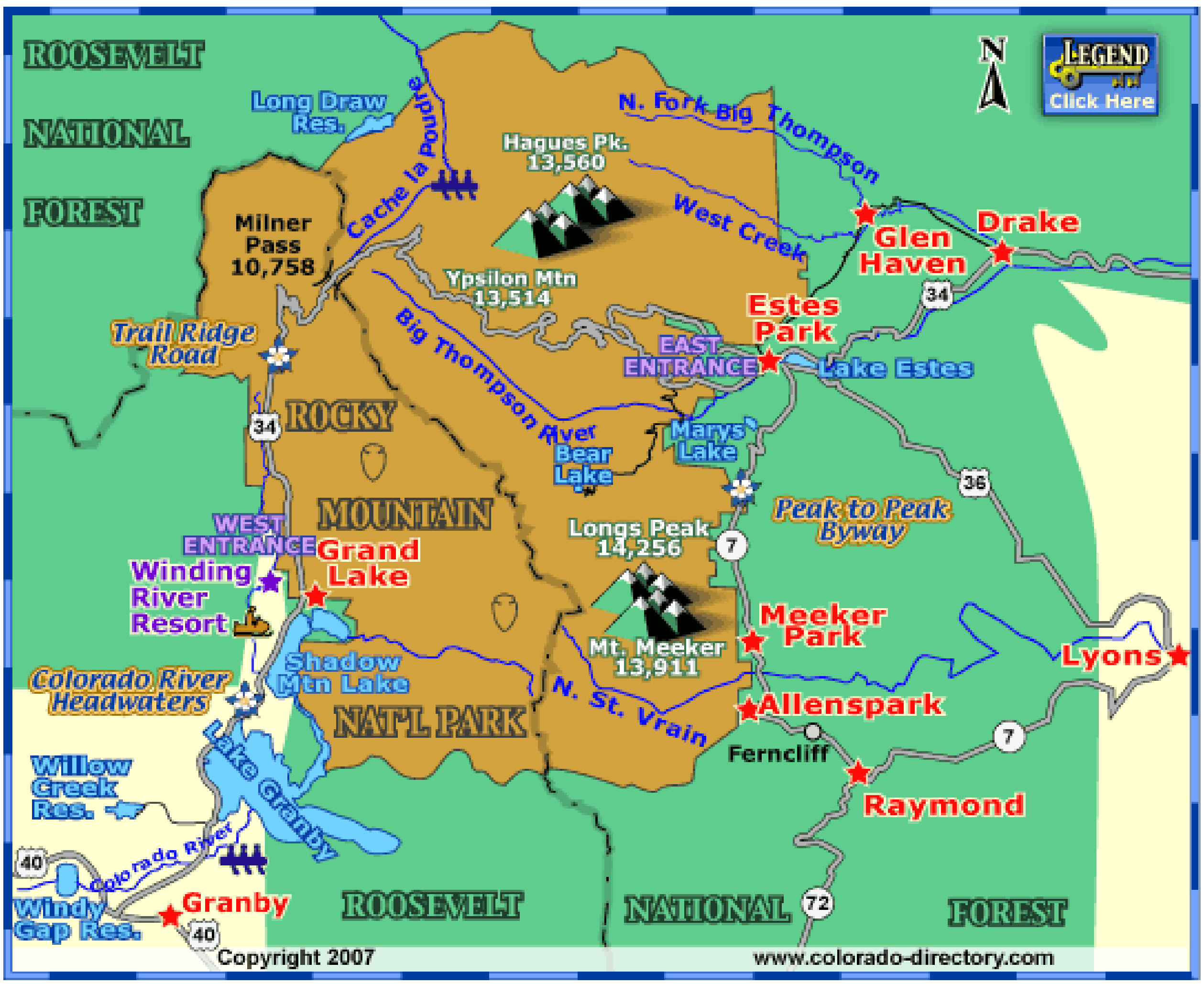

Figure 2: colorado-directory.com

Geologic Setting of Rocky Mountain National Park

The geologic history of Rocky Mountain National Park includes three orogenic events, erosion and uplifting, faulting, inland seas, and three major glaciations. Evidence of each geologic event can be found within Rocky Mountain National Park.

COLORADO GEOLOGIC TIME SCALE

Era	Period	(millions of years ago)	Major Geologic Events
Cenozoic	Quaternary	Present-1.8	Ice Ages Major canyon-cutting
	Tertiary	1.8-65	Large volcanic eruptions Laramide Orogeny: uplift and mountain-building
Mesozoic	Cretaceous	65-144	Dinosaurs died Interior Seaway Swamp conditions Coals and shales deposited
	Jurassic	144-206	Desert conditions Submergence and salt flats
	Triassic	206-248	Dinosaurs roamed
Paleozoic	Permian	248-290	Ancestral Rockies almost entirely eroded away
	Pennsylvanian	290-323	Uplift of Ancestral Rockies Erosion of older rocks and redeposition as sediments
	Mississippian	323-354	
	Devonian	354-417	Widespread shallow seas Periods of erosion
	Silurian	417-443	
	Ordovician	443-490	
	Cambrian	490-543	
Precambrian	Accounts for more than 85% of geologic time	543-3,800?	Major igneous intrusions and metamorphism

Figure 3: NPS

→ 30,000-11,000 years ago - Pinedale Glaciers

300,000-127,000 years ago - Bull Lake Glaciers

→ 65 Ma – 28 Ma Laramide Mountain Building

→ 285 Ma – Ancestral Rockies Mountain Building

→ 1700 Ma – Precambrian Mountain Building

Precambrian Era: 3800-543 million years ago

The Precambrian Era, 3800-542 million years ago, is about 88% of earth's history. There is not a major extinction event that ends the era, but an explosion of the first life 3.5 billion years ago starting to develop from the single celled organisms.

Geologic Era	Time Period	Rocky Mountain National Park Evidence
Precambrian	3800-543 million years ago	- Crystalline basement rock created - Ancient Rockies Orogeny - Major igneous intrusions and metamorphism -Boulder Creek Batholith -Silver Plume Granite intrusion

Several events happened in the Precambrian Era to create the rock formations seen in Rocky Mountain National Park. The oldest rocks in Rocky Mountain National Park come from the Precambrian Era and date back 1.7 billion years. The parent rocks include sedimentary shale, sandstone interbedded with plutonic granites. The Precambrian orogeny that created the Ancient Rockies increased tectonic activity, compressed, folded, uplifted and metamorphosed the parent rocks into a variety of metamorphic schist and gneiss rocks. The metamorphosed rocks can be seen along the Continental Divide and Trail Ridge Road. The schist and gneiss of Rocky Mountain National Park show evidence the tectonic activity occurred repeatedly during the Precambrian Era. The tectonic activity also created major faults that are significant to the Rocky Mountains you see today. About 1.6 billion years ago a massive igneous intrusion known as the Boulder Creek Batholith pushed into the schist and gneiss basement rock creating regional metamorphism. The batholith extended about 30 miles across Rocky Mountain National Park. Contacts between the granitic intrusions and metamorphic rock can be seen on canyon walls east of the Continental Divide. This event is separate from the worldwide intrusion 1.4 billion years ago that is evident in Rocky Mountain National Park.

Paleozoic Era: 543-248 million years ago

The Paleozoic Era occurred 542- 251 million years ago. The prefix paleo means past and this era encompasses the first land plants, first fish, organisms with shells, insects, amphibians, and the dominate trilobites. The major extinction that ended the Paleozoic Era is the Permian- Triassic extinction. During the extinction 50% of all animal families went extinct, and 95% of all marine species went extinct.

Geologic Era	Time Period	Rocky Mountain National Park Evidence
Paleozoic	543- 248 million years ago	- Inland sea advancement and retreats - Ancestral Rockies Orogeny - Ancient Rockies eroded away

After the Ancient Rockies formed1.7 billion years ago, Rocky Mountain National Park was covered with sediment from inland seas for about 200 million years in the Early Paleozoic. Erosion and the Ancestral Rockies orogeny took the bedrock away creating a major unconformity. About 300 million years ago in the Late Paleozoic Era, the Ancestral Rockies formed west of the Front Range today. The Ancestral Rockies were about 2,000 feet high and extended from Boulder to Steamboat Colorado. The Ancestral Rockies orogeny was elevated along faults in the Precambrian crystalline basement rock. There is little evidence of the Paleozoic Era within Rocky Mountain National Park and what is known is from studying the upturned layers of sedimentary rock just outside the park.

Mesozoic Era: 248- 65 million years ago

The Mesozoic Era occurred 251- 65 million years ago. The prefix Meso means middle and this era is also known as the time of dinosaurs. During the Mesozoic Era the first flowering plants and birds appear on earth. The extinction event that ended the Mesozoic Era is known at the Cretaceous-Tertiary. During this extinction event 50% of marine and land life forms died out, including the dinosaurs.

Geologic Era	Time Period	Rocky Mountain National Park Evidence
Mesozoic	248-65 million years ago	- Ancestral Rockies erosion - Western Interior Seaway Advancement and retreat - Beginning of Laramide Orogeny

By the beginning of the Mesozoic Era most of the Ancestral Rockies eroded away and Rocky Mountain National Park slowly became covered by water and sediment from the advancement and retreatment of the Western Interior seaway. In the Late Mesozoic Era, Cretaceous Period 100 million years ago, the Western Interior seaway advanced to completely cover Rocky Mountain National Park accumulating several hundred feet of sediment. This is evident in Rocky Mountain National Park east of Lead Mountain, and on the summits of Howard Mountain and Mount Cirrus in the Never Summer Mountains. The inland sea was followed by the Laramide orogeny beginning about 70 million years before present.

Cenozoic Era: 65 million years ago- present day

The Cenozoic Era, 65 million years- present day, is the era of today. The prefix ceno means current. We are still in the Cenozoic Era because the earth has not experienced a mass extinction event.

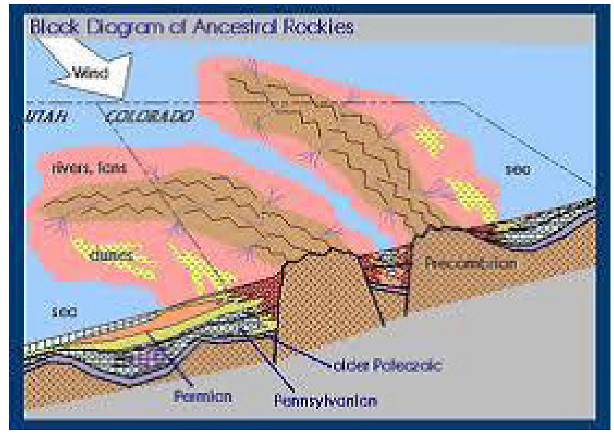

Figure 4: jan.ucc.nau.edu

Geologic Era	Time Period	Rocky Mountain National Park Evidence
Cenozoic	65 million years ago- present	- Continuation of Laramide Orogeny - Volcanism - Glaciation events -Bull Lake Glaciation -Pinedale Glaciation -Satanta Peak advance - Mass wasting and erosion

Tertiary Period: 65-2.6 million years ago

The first and most significant geologic event that shaped Rocky Mountain National Park in the Tertiary Period is the Laramide orogeny. The Laramide orogeny started in the Mesozoic Era 70 million years ago but the majority of the event occurring in the Tertiary Period until 28 million years ago. The Laramide orogeny involved block fault mountain building controlled to the north-northwest by the preexisting Precambrian faults. After the initial uplift there was extensive volcanism in Rocky Mountain National Park. Evidence of mudflows, ash falls, pyroclastic flows, as well as intrusive igneous rocks and extrusive igneous rocks are evidence of volcanism found in the Never Summer Mountains of Rocky Mountain National Park. The most recent Tertiary event is a combination of erosion and faulted uplifting. The uplift occurred in a series of steps on older Precambrian faults and is responsible for the Rocky Mountains modern height. The uplift disrupted the older drainage patters and created the modern drainage patterns of today. The new drainage patterns removed as much as 5000 feet of sedimentary rocks from earlier inland seas deposits. This erosion exposed the basement rock of the Ancestral Rockies. Evidence of the uplifting and erosion can be found on the way to Rocky Mountain National Park in the hogbacks of the Front Range foothills.

Quaternary Period: 2.6 Million years ago- present

The major geologic process that shaped Rocky Mountain National Park in the Quaternary Period was glaciers. The first glacial event is the Bull Lake that occurred 300,000- 127,000 years ago. Bull Lake is further broken down into the Early Bull Lake, 300,000- 200,000 years ago, and Late Bull Lake, 200,000- 127,000 years ago. Evidence of Bull Lake can be found within Rocky Mountain National Park at Bierstadt Lake, west of the Beaver Meadows entrance, south of Sandbeach Lake, and east of Copeland Mountain. The second glacial event in Rocky Mountain National Park is the Pinedale glaciation. Pinedale occurred 30,000- 12,000 years ago, reaching a maximum 23,500 years before present. Pinedale is the last true valley glaciation to affect the Front Range. Evidence within Rocky Mountain National Park of the Pinedale glaciation can be found at Moraine Park and Horseshoe Park, as well as Wild Basin and Kawuneeche Valley. In the Late Pleistocene a minor glaciation event called the Satanta Peak advance occurred about 10,000 years before present. The most recent geologic activity in Rocky Mountain National Park is stream erosion starting 3,800 years before present. Evidence of stream erosion is seen throughout Rocky Mountain National Park by the v- shaped valleys. The best recent example of stream erosion in Rocky Mountain National Park is the alluvial fan that was deposited in the Lawn Lake Flood of 1982.

Tectonics of Rocky Mountain National Park

Tectonic Principles relevant to Rocky Mountain National Park

There are some important tectonic principles to know in order to understand the process of building the Rocky Mountains. First, it is important to recognize the difference between the hard basement layer of crystalline rock, and the easily erodible cover layer of sedimentary and igneous rocks. The mechanical strength of the crystalline basement rock is directly proportional to how much the Earth crust can support a geologic feature. The mechanical strength of the Rocky Mountain crystalline basement is particularly strong because it supports a geologic feature as big as the Rocky Mountains. The basement rock has planes of weaknesses in faults and shear zones that influence building of the current Rocky Mountains.

Second, isostasy is the ideal balance of large portions of Earth's crust. It controls the regional elevations adjacent to Rocky Mountain National Park by elevating the area on east and west of the mountains to account for the weight of the Rocky Mountains. Without the strength of the basement crystalline rock and isostasy the Earth's crust would not be about to support the Rocky Mountains.

Plate Tectonics

The plate tectonics of Rocky Mountain National Park started 1.7 billion years before present and include mountain uplifting, erosion, inland seas and localized deformation. The current Rocky Mountains can be explained by plate tectonics as intraplate deformation by a combination of low angle subduction of the Farallon Plate to the west, and regional uplift and extension to the south-southwest by the Rio Grande Rift.

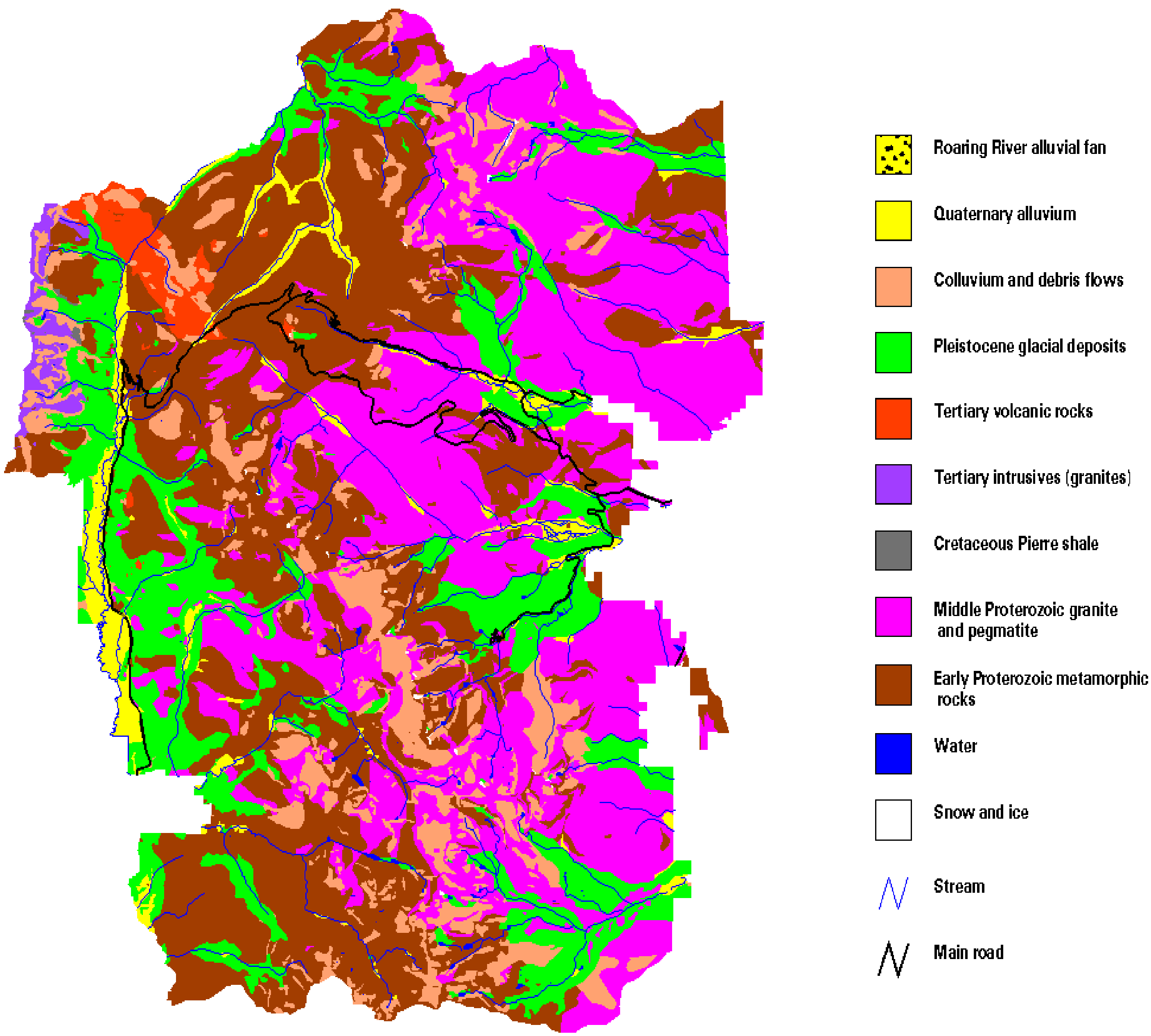

Figure 5: RMNP geologic map
geo.arizona.edu

Plate tectonics of the Precambrian Era
1.8 billion years ago- 570 million years ago

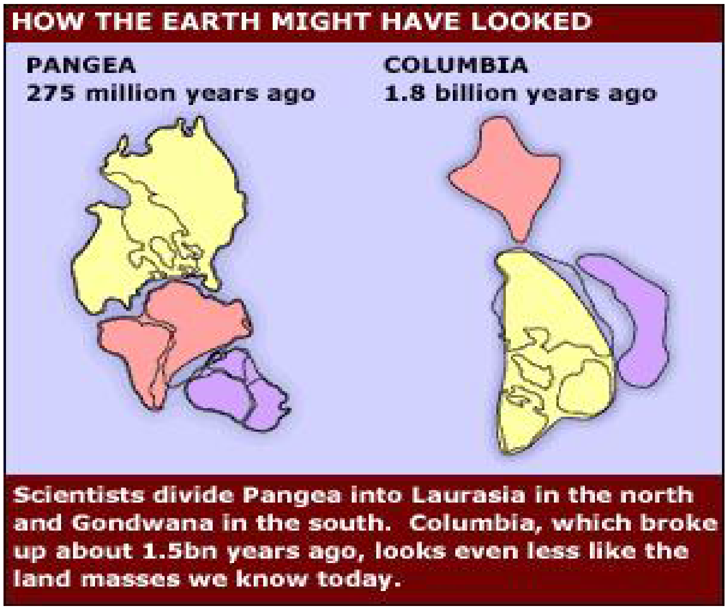

Figure 6: http://www.altacolumbia.com

1.8 billion years before present in the Precambrian Era the Colorado orogeny created the crystalline basement rock of Rocky Mountain National Park. A subduction zone collision with pieces of Wyoming cratons increased the pressure and temperature to create the metamorphic rocks that formed the crystalline basement rock of gneiss and schist. The Colorado orogeny was not the only event to create the crystalline basement of the Rocky Mountains. The Berthoud orogeny, 1.4 billion years before present, was the second step in creating the crystalline basement of Rocky Mountain National Park. A subduction zone to the south created a ductile shear zone and numerous plutons in the Rocky Mountain chain. Known as the Berthoud orogeny, these plutons make up of 20-30% of the basement rock and extend far beyond Rocky Mountain National Park. The specific type of Berthoud granite that is exposed in Rocky Mountain National Park is the Silver Plume granite. The Silver Plume granite was brought the surface by continental rifting and uplifting that ended in the Late Proterozoic 600 million years ago. The Silver Plume granite can be seen throughout Rocky Mountain National Park by the rounded granite tops of Lumpy Ridge. Other intrusions of the Berthoud orogeny in Rocky Mountain National Park are Hagues Peak granite found in the Mummy Mountains, multiple mafic dikes and pegmatite throughout the park, the Iron Dike near Mount Chapin and Storm Pass north of Trail Ridge Road.

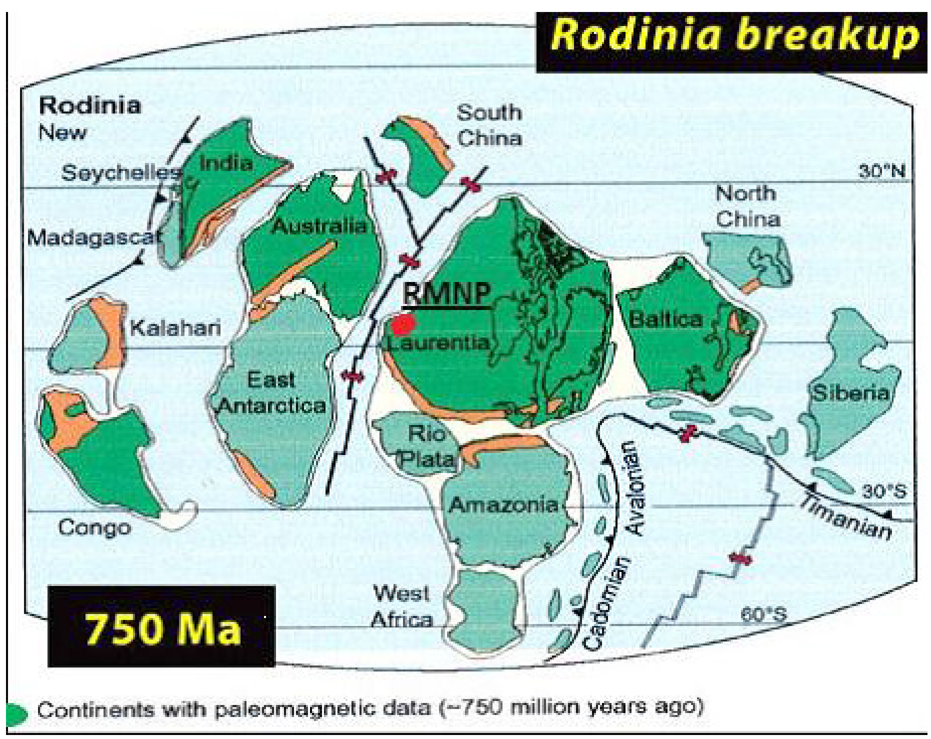

Figure 7: © Snowball Earth.org

At the Precambrian-Cambrian boundary Rodinia broke apart re-assembled to form Pangaea. Geologists further divide Pangaea into Laurasia to the north, and Gondwana to the south. The coast of western North America was created when Gondwana rifted away from Rodinia's southwest margin around 750 million years before present. The rifting created low lying mountains, mass wasting and erosion, with the eventual formation of shallow inland seas. The rifting ending about 600 million years ago but the faults created define the Rocky Mountains millions of years later.

The Great Unconformity

Figure 8: I-70 and Glenwood Canyon, Colorado. Steven Dutch, Natural and Applied Sciences, University of Wisconsin- Green Bay

After the creation of the crystalline basement and before the rifting away of Gondwana the Rocky Mountains are a mystery. Known as the Great Unconformity, Earth's history from 1.4 billion years to 600 million years is missing from the stratigraphic column of the Rocky Mountains. Any surface deposited in Colorado before 600 million years before present, except the crystalline basement, has been erased by erosion to create the Great Unconformity. The Great Unconformity leaves unanswered questions of the plate tectonics of the Rocky Mountains in the Precambrian Era.

Plate tectonics of the Paleozoic Era 570-290 million of years ago

Before the Cambrian period, all the evidence of Rocky Mountain National Park is lost in the Great Unconformity. The Rocky Mountains history begins to show record again in the Late Cambrian, 510 million years ago. Shallow tropical seas spread over Rocky Mountain National Park and 6,000-12,000 feet of marine sediments accumulated over the eroded surface of the Precambrian crystalline rocks. The sediment accumulated continued into the early Pennsylvanian 300 million years ago. In the Devonian, 360 million years before present, the eastern margin of Laurasia collided with a microcontinent Avalonion and created the Appalachian Mountains in the Alleghenian orogeny. The effects of the Alleghenian orogeny caused a massive uplift of the Colorado region that impacted the Rocky Mountains.

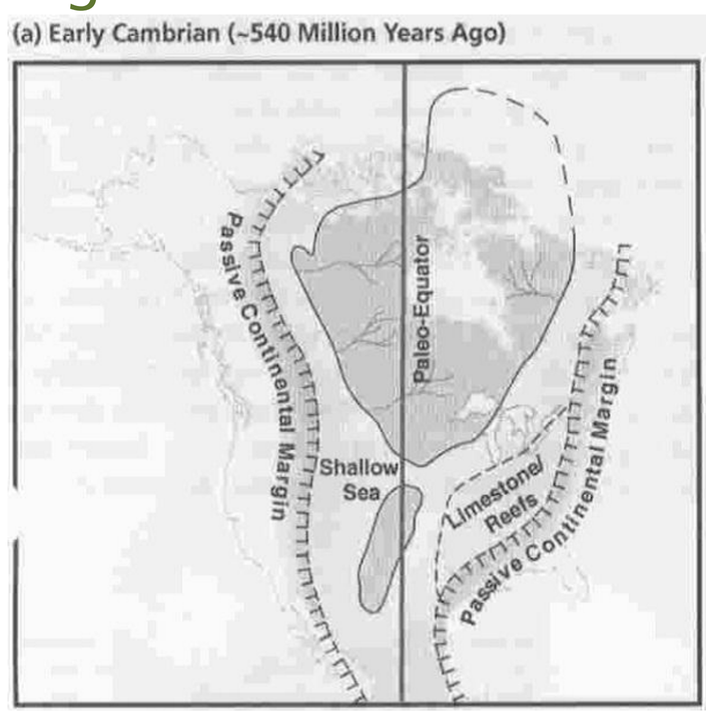

Figure 9: shallow Sea advancing over the North American Craton 540 million years before present (Robert J. Lillie)

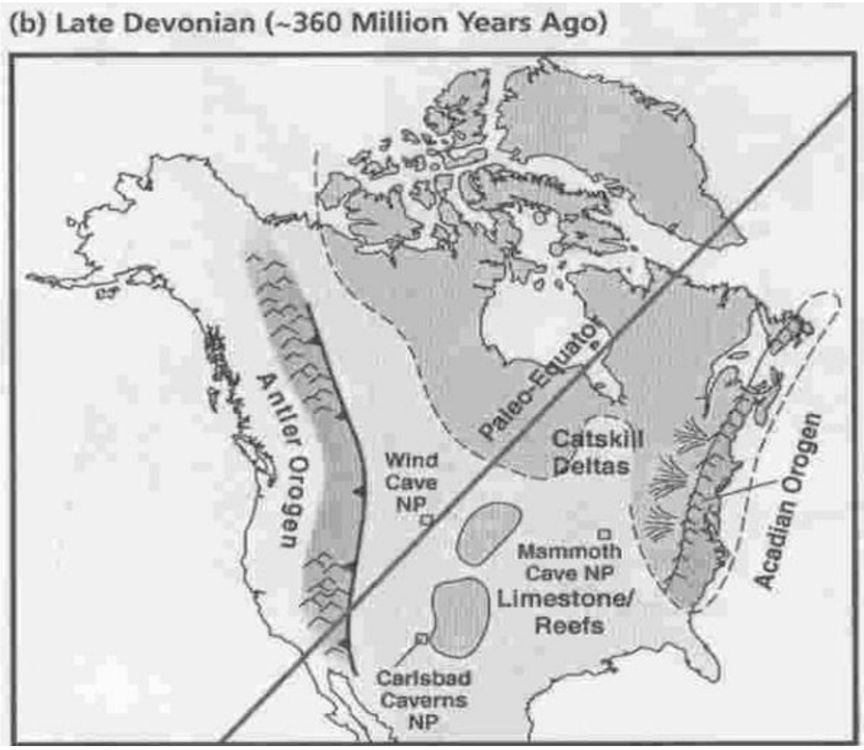

Figure 10: shallow sea advancing over the North American Craton 360 million years before present (Robert J. Lillie)

The impact was strong enough to activate the Precambrian faults in the crystalline basement and uplifted the Ancestral Rocky Mountains. The Ancestral Rocky Mountains are broken down to Frontrangia to the east, and Uncompahgria in southwestern Colorado. The Ancestral Rocky Mountains uplifted with a northwest- southeast trend by faulted anticlines and steep reverse faults set by the Precambrian crystalline basement. Erosion eventually removed the sediment cover and part of the basement rock. Sediments were transported east of Frontrangia and accumulated in central and eastern Colorado. Sediments from Uncompahgria washed the west and accumulated in southwestern Colorado. By the end of the Permian, 248 million years before present, the Ancestral Rockies were almost eroded away and the evidence is now found in the foothills just east of Rocky Mountain National Park.

Plate Tectonics of the Mesozoic Era 248- 65 million years ago

In the early Triassic, 248 million years before present, the Ancestral Rocky Mountains were almost eroded away completely. Colorado was above water in the Triassic but there was little surface relief left from the Ancestral Rocky Mountains. The low lying relief was covered when the climate changed to warm tropical. As a result Rocky Mountain National Park, and most of Colorado, was a desolate mudflat area. In the early Jurassic, 206 million years before present, there was another change from mudflats to desert dune fields, back to mudflats, and back again to a desert environment. By the end of the Jurassic Pangaea had broken apart and plate tectonics moved Colorado to its present latitude. Colorado was flat and barely above sea

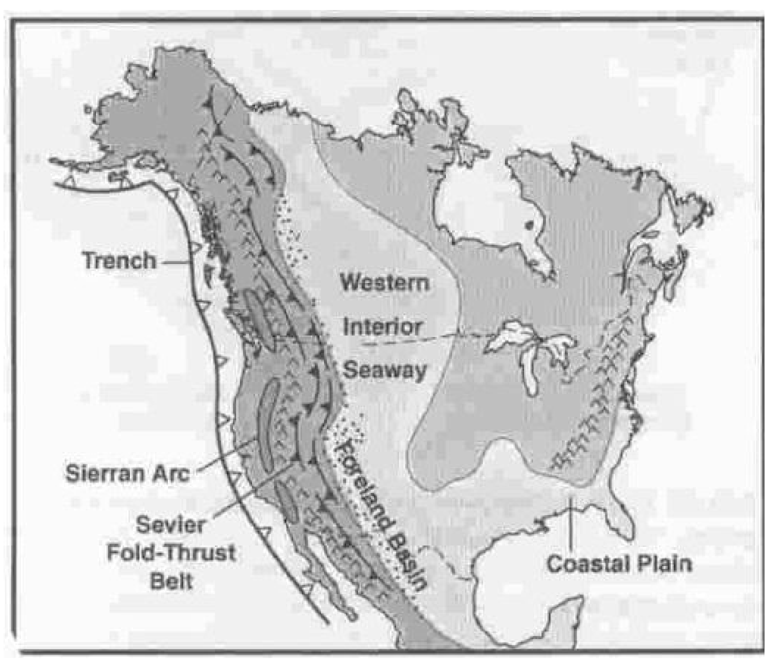

Figure 11: Western Interior seaway (Robert J. Lillie)

level as the climate became moist again. The Western Interior seaway started its advancement in the early Cretaceous and reached its maximum about 90 million years ago in the Mid Cretaceous. The Western Interior seaway stretched west to central Utah and reached east to the Appalachians, extended north to the Arctic and south to the Gulf of Mexico. During this time Rocky Mountain National Park was covered by at least 600 feet of water. The Late Cretaceous was the last time Rocky Mountain National Park was covered with as much water and sediments because 70 million years ago the Laramide Orogeny started and uplifted the Rocky Mountains as we know them today.

Plate Tectonics of the Cenozoic Era 65 million years ago- Today

Starting in the Late Cretaceous, 70 million years before present, the Laramide orogeny did a majority of work in the Tertiary Period of the Cenozoic Era lasting until 35 million years before present. The origin of the Laramide orogeny is from low angle, flat slab subduction of the Farallon Plate under the North American Plate. Prior to the Laramide orogeny, the Farallon plate was subducting at a typical angle of 30 degrees. The crustal plate changed to flat slab subduction of an angle less than 10 degrees. Geologist theorized the reason for the change of subduction angle is to account for a change in rate of subduction, and/or change to a more buoyant plate material. The result is the Rocky Mountains building 500-700 miles inland, not the 100-250 miles normally seen at subduction zones. The Rocky Mountain chain is located in the central part of the continent because of the flat slab subduction and a weakness in the crust extending the North American continent. The rift section directly affecting Rocky Mountain National Park is known as the Rio Grande Rift. The current rift is a result of the extension and stretching to the west in the Basin and Range area and originated near the end of the Laramide orogeny in the Mid Tertiary about 28 million years ago. Before the Laramide orogeny uplifted the current Rocky Mountains there was low relief thousands of feet of sedimentation. As the Laramide orogeny uplifted the Rocky Mountains, the sediment weathered and eroded downslope. These sediments can be observed today as the hogbacks at the foothills of Rocky

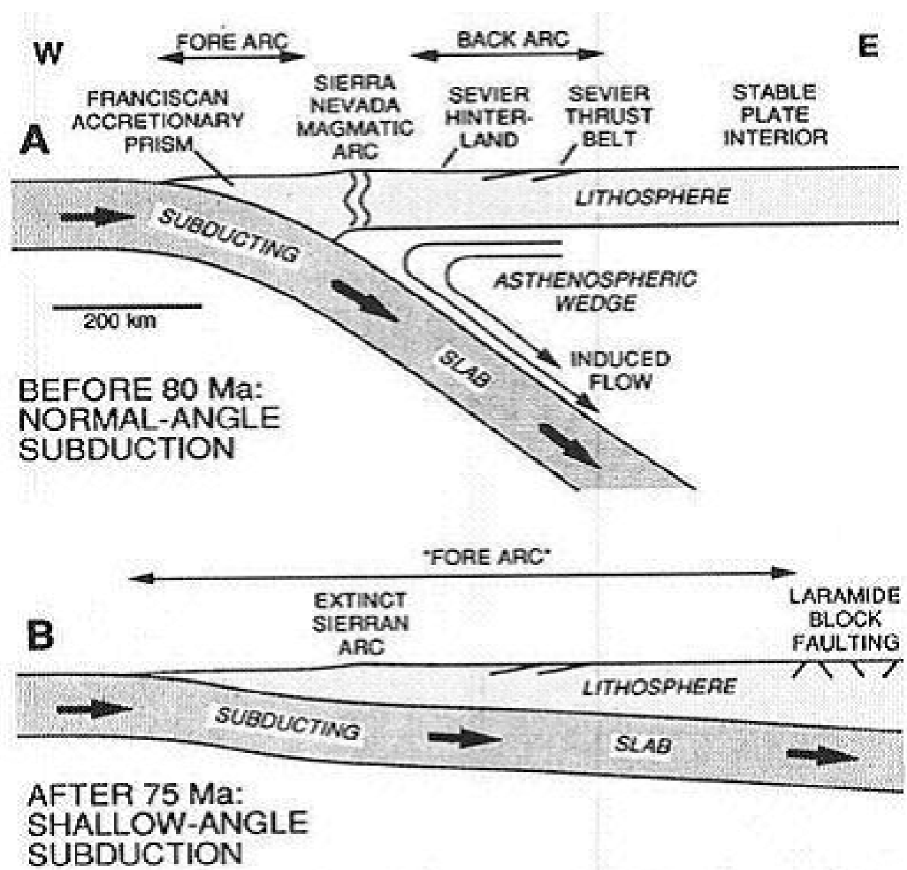

Figure 12: Dumitru et al., 1991

Mountain National Park. The hogbacks are clearly seen driving east out of Rocky Mountain National Park from Loveland on U.S. 34. Rock descriptions of the foothill formations can be found in the appendix.

The Laramide orogeny not only removed the sediment from Rocky Mountain National Park but also produced a volcanic event that started 30 million years before present. Lava flows at Mt. Richthofen are evidence of the first part of the volcanic event. The later volcanic event occurred 27 million years before present and is preserved in Rocky Mountain National Park near Specimen Mountain as mudflows, lava flows and obsidian. A layer of volcanic ash and rhyolite tuff can be seen near Iceberg Lake along Trail Ridge Road. After the Laramide orogeny and the volcanic intrusions, another uplift event occurred. Erosion eventually removed most of the volcanic and all of the sedimentation evidence in Rocky Mountain National Park.

The most recent tectonic history of Rocky Mountain National Park is the uplifting of the Front Range. The Precambrian faults activated again to raise Rocky Mountain National Park 4000-6000 feet and drop areas like Estes Park 1000 feet. This last uplifting event began 2.6 million years ago and is responsible for the current drainage patterns of the Continental Divide. This uplifting, along with worldwide climate change, was also responsible for glaciation events that sculpted Rocky Mountain National Park.

Glaciers of Rocky Mountain National Park

Glacier history is evident everywhere in Rocky Mountain National Park. Glaciers are responsible for how Rocky Mountain National Park is sculpted with meadows and mountains. Glaciations are a response to the climate and tectonic processes, without both aspects working together glaciers cannot exist. Glaciations of Rocky Mountain National Park are: Bull Lake glaciation, 300,000-127,000 year ago, Pinedale glaciation, 30,000-12,000, Satanta Peak glaciation, 14,400-10,000 years ago and the current Neoglaciation which started 3,800 years ago.

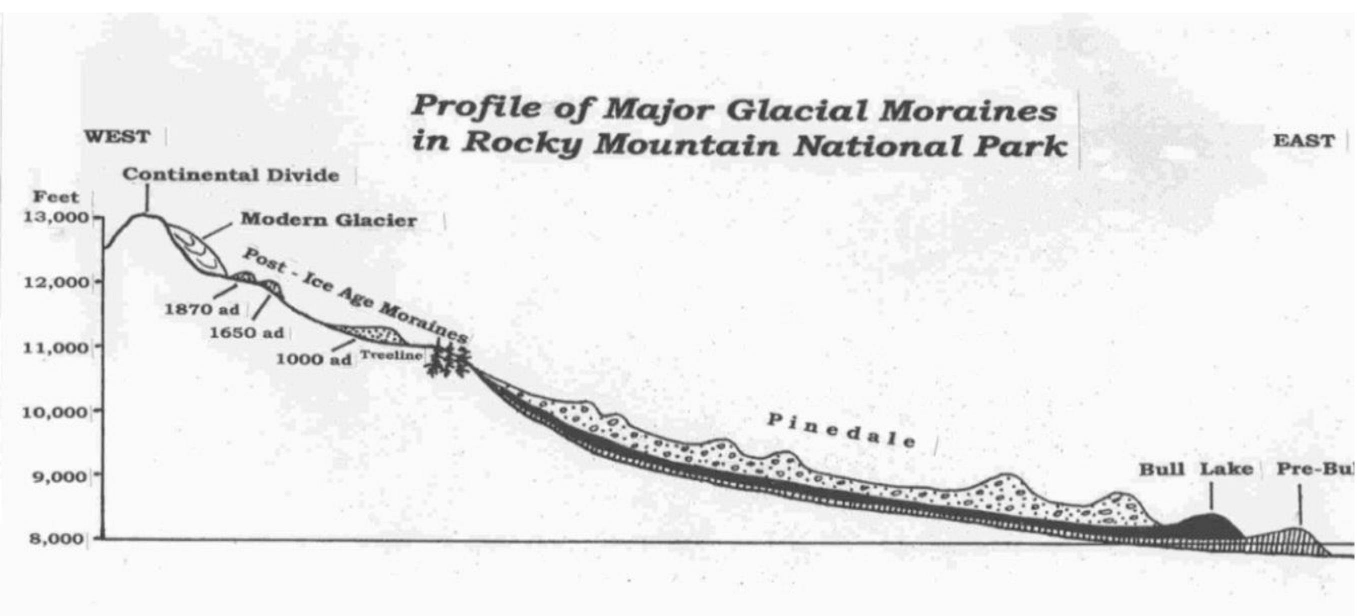

Figure 13: NPS

Pre-Bull Lake- 1.2 million years ago

The Pre-Bull glaciation occurred before the Bull Lake glaciation starting 1.2 million years ago. Pre Bull Lake had 2 major advances; however most of the Pre-Bull glaciation evidence was removed by later glaciations. Some deposits are found outside the eastern boundary of Rocky Mountain National Park along highway 7 near the Fall River entrance. Most evidence found in Rocky Mountain National Park is evidence from later glaciation events.

Bull Lake glaciation- 300,000-127,000 year ago

The Bull Lake glaciation is broken down in the early Bull Lake that occurred 300,000-200,000 years ago and the late Bull Lake occurred 200,000-127,000 years ago. Bull Lake glacier tributaries started high in the Rocky Mountains and joined together in lower elevations to create large massive glaciers that sculpted Rocky Mountain National Park. Both advances of the Bull Lake glaciation sculpted the same cirque basins and canyons leaving behind similar moraine evidence. To distinguish between the late Bull Lake and early Bull Lake glaciation geologists use degree of weathering and different moraine features. The terminal moraines of the early Bull Lake glacial advance consist of brown, silt and sand deposits containing pale-gray stones. The deposits of the late Bull Lake advancement overlie the weathered deposits of the early Bull Lake advancement. These deposits contain pale brown silty sand with stones of different sizes and degrees of rounding. Some of the rocks in the moraines show glacial striations, however, boulders are usually not found within these moraines. On the west side of the park, Bull Lake glaciers occupied the Colorado River Valley and deposited a terminal moraine directly south of Shadow Mountain Lake. This terminal moraine has a high degree of weathering and is consistent with other Bull Lake evidence. The Shadow Mountain moraines contain large amounts of volcanic rock carried down by the glacier from the Never Summer Mountains. The glaciers from the Never Summer Mountains merged with the glaciers in the Colorado River Valley to reach 20 miles long,extending from the La Poudre Pass to Shadow Mountain Lake. Other evidence of Bull Lake can be seen in east side of Rocky Mountain National Park at Aspenglen Campground and near the Beaver Meadows entrance.

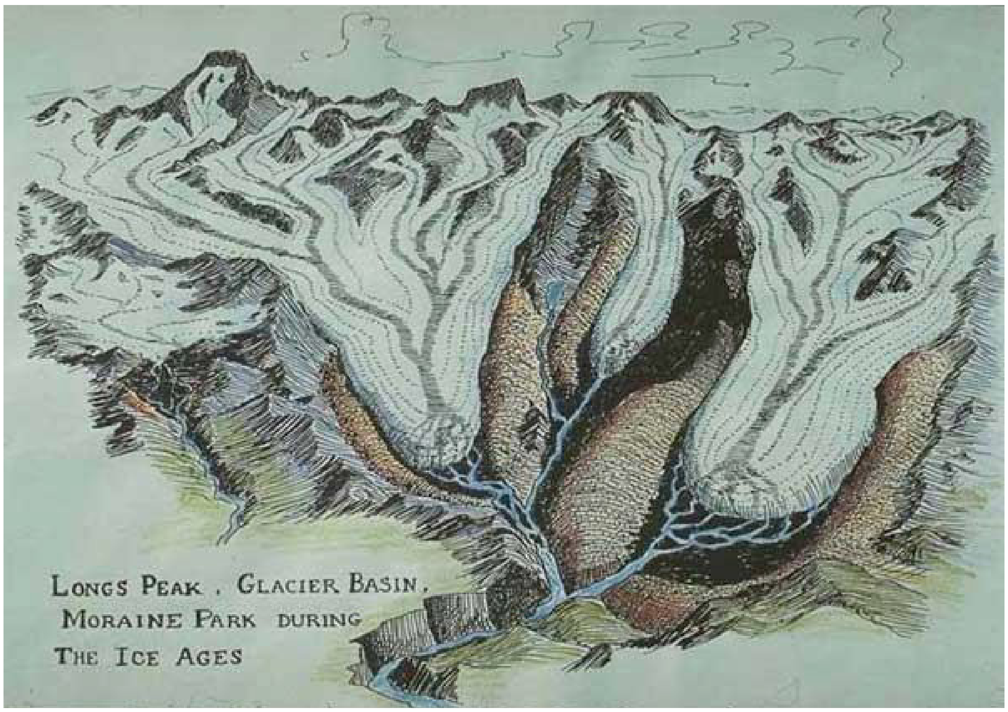

Figure 14: 14ers.com

Pinedale glaciation- 30,000-12,000 years ago

The Pinedale glaciation occurred 30,000-23,500 years ago and makes up the majority of glacial evidence in Rocky Mountain National Park. Not as extensive as Bull Lake, the Pinedale glaciation reached a maximum 23,500- 20,000 years ago; then between 15,000- 12,000 years ago the glaciers started to recede. By 10,000 years before present all Pinedale glaciers were melted.
The Pinedale glaciation sculpted the alpine peaks and large flat valleys in Rocky Mountain National Park. As a relatively recent event, landforms shaped from the Pinedale Glaciation are less weathered and eroded, showing sharper ridges. Pinedale glacial moraines have more surficial boulders than older moraines. These boulders were exposed from the Pinedale event carving into preexisting valleys created by previous glacial periods. The Pinedale glaciation started in the alpine and gouged out mountain peaks creating cirque headwalls and vertical faces like the diamond of Longs Peak. The higher elevation glaciers also created rock basin lakes seen in Tyndall Gorge and Loch Vale. The boulders were carried down to the valley floor and deposited in the moraines. On the west side of Rocky Mountain National Park a glacier 20 miles long extended west of Le Poudre pass south to the morainal islands of Shadow Mountain Lake.

Figure 15: Moraine Park view from Many Parks Curve

The Pinedale glaciation Fall River glacier which sculpted the u-shaped valley of Horseshoe Park, the 13 mile long Thompson glacier occupied Big Thompson valley and carved Moraine Park. Enclosed by the lateral moraines and terminal moraines, ice started to melt creating glacial lakes that filled the valley floors with small sediment.

The different terrain and vegetation of the moraines compared to the valley floor is a result of glacial lakes. Fine sediment, which settled in glacial lake beds on the valley floor, fosters conditions for grasses to grow. Coarser sediment which comprises the moraines provides habitat for larger tree growth. Evidence of the Pinedale glaciation also include cirque lakes Chasm Lake and Mills Lake, and kettle pond formations Sheep Lakes. Several Mountains top horns, cols and arête are seen high in the alpine. The best example of a horn is the Little Matterhorn in Glacier Gorge and cols can be found above Andrew Glacier in Loch Vale.

A roche moutonnee is evident in the Glacial Knobs area and Moraine Park. Erratics are abundant at the talus field and along Cub Lake trail. Glacial pavement and striations are seen near North Inlet and along Fall River Road. Everywhere you look in Rocky Mountain National Park you can find evidence of the Pinedale glaciation.

Post- Pleistocene Glaciation

Today there is not extensive glaciation in Rocky Mountain National Park and post- Pleistocene ice accumulation is only found within cirques. The evidence of post- Pleistocene glaciations is easier to identify because the weathering is less extensive than older glacial evidence. The evidence is found high in the alpine because the glaciers do not advance very far due to the colder climate.

The Satanta Peak advance began to about 14,400 years ago and ended about 10,000 years ago. The Satanta Peak advance was a cirque- glacier advance with the furthest advancement occurring after the large valley Pinedale glaciers disappeared. Evidence in Rocky Mountain National Park of the Satanta Peak glaciation advance can be seen at Sky Pond and the moraine in Loch Vale.

Ice accumulation during Holocene time was given the name Neoglaciation also known as the “Little Ice Age” because the ice advancement was not extensive enough to be considered a full ice age. The ice deposits found in Rocky Mountain National Park record four intervals of ice accumulation. The ice accumulations are the Ptarmigan, 7,250–6,380 years ago, Triple Lakes, 5,200–3,000 years ago, Audubon, 2,400–950 years ago, and Arapaho Peak 350–100 years ago.

The Ptarmigan advance represents a brief reversal of the warming trend that had begun about 10,000 years ago. The Triple Lakes accumulation was the most extensive. Like modern glaciers, Audubon and Arapaho Peak glaciers depended on wind- drifted snow for their existence.

Figure 16: protrails.com Andrews Tarn and Andrews Glacier

Currently there are 34 snow banks and ice masses near Rocky Mountain National Park. Fourteen of the ice masses are located in Rocky Mountain National Park: Rowe Glacier, located between Rowe Peak and Hagues Peak, Sprague Glacier, at Irene Lake in Spruce Canyon, Tyndall Glacier placed at the head of Tyndall Creek, Andrews Glacier which can be seen east of Andrews Pass, Taylor Glacier, at the head of Icy Brook, Chiefs Head Peak Glacier above Frozen Lake, Mills Glacier on the east side of Longs Peak, Moomaw Glacier on the south of The Cleaver. There are six St. Vrain Glaciers located outside of the park at the head of Middle St. Vrain Creek. Only the ice mass above Murphy Lake near Snowdrift Peak is on the east side of the Continental Divide and all but one ice mass occur on north or east facing cirques. The exception is the large snow bank northeast of Rowe Mountain. Some of the ice masses, such as Andrews Glacier, are actively moving and can be considered actual glaciers. Winter winds blow snow over the Continental Divide where the snow drifts into cirques. The process of snow deposition gives these "wind drift glaciers" their name and is the majority of modern glaciers in Rocky Mountain National Park.

Rock Glaciers

Rock glaciers are left by retreating ice glaciers. The rocks contain enough ice to still be affected by freezing and thawing, pushing the rock glacier down slope over time. Rock glaciers are hard to recognize on the ground because they look like a rock field or talus slope. Rock glaciers flow downhill at speeds up to 1-2 m/year, however, rock glaciers in Rocky Mountain National Park have been clocked at 13-20 cm/year. Rock glaciers exist below Taylor and Tyndall glaciers, as well as other locations without glaciers.

Erosion History of Rocky Mountain National Park

Erosion processes are a direct response to the tectonic and glacial history of Rocky Mountain National Park. Without erosion removing thousands of feet of sediment the Rocky Mountains would look dramatically different than what you see today. Before the Ancestral Rockies could finish rising, erosion began to change the growing topography of Rocky Mountain National Park. During the Mesozoic Era the major advancement of the Western Interior seaway accumulated about 10,000 feet of

Figure 17: rmnp.com View from Rainbow Curve looking at Horseshoe Park.

sedimentary rock in Rocky Mountain National Park. The sediments washed away with the uplift of the modern Rocky Mountains during the Laramide orogeny 70 million years before present. The crystalline basement rock was uncovered and v- shaped valleys were carved by mountain streams. The sediment was displaced and is now the foothills of Rocky Mountain National Park. Remnants of Cenozoic Era, Tertiary period erosional surfaces are preserved in the level tops of mountains above timber line in Rocky Mountain National Park. The erosion surface forms the top of Flattop Mountain and the entire rolling upland has been named Flattop peneplain, meaning almost a plain. The erosion surface now stands 11,500 to 12,000 feet in elevation and was raised by a series of uplifts which did not fold or distort them. The summits of Deer Mountain and The Needles are another example of an erosion surface that now stands about 10,000 feet. The granite in Rocky Mountain National Park is susceptible to exfoliation joint weathering, creating exfoliation domes that can be seen on McGregor Mountain and throughout Lumpy Ridge. The last uplifting event was before the last glaciation event, resulting in the terrain of Rocky Mountain National Park returning v-shaped valleys with u-shaped valleys remaining on the low lying areas of Horseshoe Park and Moraine Park.

Foothills outside of Rocky Mountain National Park

Most of the sediments in the foothill formations east and west of Rocky Mountain National Park are from the Western Interior seaway of the Mesozoic Era. The same formations are on the east and west side of the Rocky Mountain National Park indicating there were no mountains when the sediments were accumulating by the Western Interior seaway. Deposited with the principle of horizontality, the sediments now make up the hogbacks of the foothills of the Front Range just outside Rocky Mountain National Park. Though the foothills formations are outside Rocky Mountain National Park, they are an important piece of geologic history of Rocky Mountain National Park. Rock descriptions of the foothill formations can be found in the appendix.

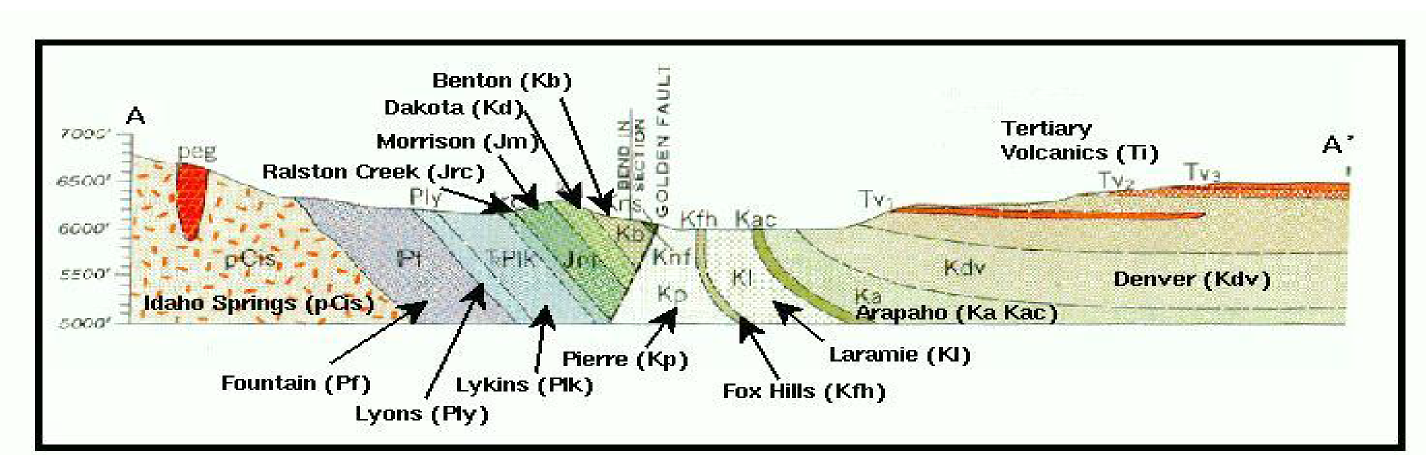

Figure 18: Amuedo and Ivey, 1978

Climate and Ecology of Rocky Mountain National Park

The climate and ecosystems of Rocky Mountain National Park is a byproduct of the geology present. Rocky Mountain National Park ranges from 7,860- 14,259 feet, and it is the range of altitudes within the park that is responsible for the different climates and ecosystems. Increase in elevation results in a decrease of temperature and a change of environment. The continental divide creates a rain shadow effect that influences the climate in Rocky Mountain National Park. The east side of Rock Mountain National Park is referred to as the dry side, where the west side is referred to as the wet side of the park. The latitudinal position of Rocky Mountain National Park also affects the climate. The north side of the park receives more snow then the south side of the park. However, a low pressure weather system known as the Albuquerque Low, which tends to affect the New Mexico area, causes particularly high snow accumulation in the southeastern region of Rocky Mountain National Park.

Climate is also related to the ecology of Rocky Mountain National Park. Climate and elevation control what plants and animals can survive. As you increase in elevation you decrease in temperature and oxygen levels. Rocky Mountain National Park has four ecosystems intertwined together in a delicate balance with the climate and geology. The four ecosystems provide homes to a variety of plants and animals that are dependent of the climate of their particular ecosystem.

The montane ecosystem is at the base of Rocky Mountain National Park and occurs up to 9,500 feet of elevation. This ecosystem tends to be relatively sunny and dry, with average temperatures of 50 degrees fahrenheit. The montane has interspersed meadows of grasses, shrubs, aspen, willow, and ponderosa pine, with moderately dense forests dominated by ponderosa and lodgepole pines. Vegetative environments are dermined by soil type and slope direction, two factors largely affected by glaciation.

The Subalpine Ecosystem occupies elevations between 9,500 and 11,000 feet. Near it's base, subalpine fir, lodgepole pine, and engelmann spruce dominate, wheras limber and whitebark pines are more common at higher elevations. Subalpine forests tend to be wet, cool, and very dense. Understories have less smaller vegatation than the montane ecosystem, but various shrubs and flowers do grow, particularly in early stages of succession, following disturbances. Soils tend to be rockier, allowing trees to drive their roots in and around large sediment for stabilization along steeper slopes experiencing harsher conditions than at lower elevations.

As elevation approaches 11,000 feet, average temperatures remain low enough that trees are unable to thrive. This is the point known as "tree line", where *krumhotlz*, or stunted, deformed, trees grow, due to lack of heat and intense winds.

Above treeline is where the alpine ecosystem of Rocky Mountain National Park emerges-- from 11,000 ft and higher. Frequent strong winds and cold temperatures limit what plants can grow is the alpine ecosystem. Cushion plants, looking like ground-hugging clumps of moss, escape the strong winds blowing a few inches above them. Many flowering plants of the tundra have dense hairs on stems and leaves to provide wind protection. Where the tundra soil is well-developed, grasses and sedges are found. Non-flowering lichens cling to rocks and soil and only photosynthesize at a temperature above 32 F. The adaptations for survival of drying winds and cold may make tundra vegetation seem very hardy, but in some respects the tundra is very fragile. Repeated footsteps often destroy tundra plants, leaving exposed soil to blow away, and recovery may take hundreds of years. The geology of the alpine is important because without the rich soil and rocks for moss and lichen to cling to, the ecosystem would not exist as it does today. The last ecosystem in Rocky Mountain National Park is the riparian. The riparian ecosystem stretches through all other ecosystems in Rocky Mountain National Park. This ecosystem is vital to the geology by creating v-shaped valleys and other erosional features.

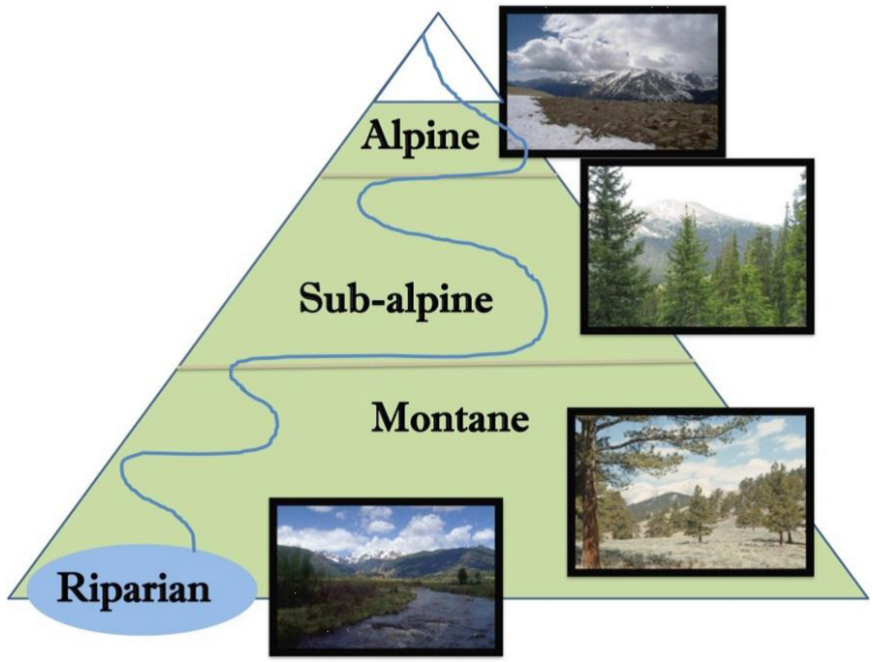

Figure 19: Alpine Sub-alpine Montane and Riparian (Image created by Jon Nicholson)

Rocky Mountain

National Park Service
U.S. Department of Interior
Rocky Mountain National Park

Geology Resources

Classroom Book List

These books are not endorsed by the National Park Service. They are intended to serve as classroom resources for students. Please be sure to preview books to ensure that they are appropriate for your classroom. This list is by no means inclusive of every book available on the topic.

<u>Elementary Level Books</u>
Crystal and Gem by RF Symes

Dave's Down-to-Earth Rock Shop by Stuart J. Murphy

First Field Guide: Rocks and Minerals by Edward Ricciuti and Margaret W. Carruthers

Earthquakes by Franklyn M. Branley

Earthquakes and Volcanoes by Lin Sutherland

Earthsteps: A Rocks Journey Through Time by Diane Nelson Spicket

Geology Rocks!: 50 hands-on activities to explore earth by Cindy Blobaum

How Mountains are Made by Kathleen Weidner Zoehfeld

Rocking and Rolling by Philip Steele

Rocks by Alice K. Flanagan

Sand by Ellen Prager

Planet Earth by Barbara Taylor

The Magic School bus Blows its Top by Joanna Cole

Volcano by Anne Rooney

<u>High School Level Books</u>
Geology Along Trail Ridge Road: A Self-Guided Tour for Motorists by Omer B. Raup

Geology Underfoot Along Colorado's Front Range by Lon Abbott and Terri Cook

Hiking Colorado's Geology by Ralph Lee Hopkins and Lindy Birkel Hopkins

Messages in Stone: Colorado's Colorful Geology edited by Vincent Matthews, Katie KellerLynn and Betty Fox

Roadside Geology of Colorado by Halka Chronic

Rock Formations and Unusual Geologic Structures Exploring the Earht's Surface by Jon Erickson and Ernest H Muller

Rocks and Minerals, National Audubon Society North American Field Guide

The Field Guide to Geology by David Lambert

Glossary

Ablation - As applied to glacier ice, the process by which ice below the snow line is wasted by evaporation and melting.

Alluvial fan - An assemblage of sediments marking place where a stream moves from a steep gradient to a flatter gradient and suddenly loses transporting power. Typical of arid and semiarid climates but not confined to them.

Andesite - A fine-grained volcanic rock of intermediate composition, consisting largely of plagioclase and one or more mafic minerals.

Anticline - A fold that is convex upward, or that had such an attitude at some stage of its development.

Aphanitic- A textural term meaning "fine-grained" that applies to igneous rocks.

Archean - An eon of geologic time extending from about 3.9 billion years to 2.5 billion years ago.

Arête - A narrow, saw-toothed mountain ridge developed by glacier erosion in adjacent cirques.

Arkose - A sedimentary rock formed by the cementation of sand-sized grains of feldspar and quartz.

Asthenosphere - The weak or "soft" zone in the upper mantle just below the lithosphere, involved in plate movement and isostatic adjustments. It lies 70 to 100 km below the surface and may extend to a depth of 400 km.

Aureole - A zone surrounding an igneous intrusion, in which contact metamorphism has taken place.

Basalt - A dark colored extrusive igneous rock composed chiefly of calcium plagioclase and pyroxene.Extrusive equivalent of gabbro, underlying the ocean basins and comprises oceanic crust.

Basin - A synclinal structure, roughly circular in its outcrop pattern, in which beds dip gently toward the center from all directions.

Batholith - A large, discordant, intrusive body of igneous rock.

Bed load - Material in motion along a stream bed.

Bedding - A collective term used to signify presence of beds, or layers, in sedimentary rocks and deposits.

Bedding plane - Surface separating layers of sedimentary rocks and deposits. Each bedding plane marks termination of one deposit and beginning of another of different character, such as a surface separating a sandstone bed from an overlying mudstone bed. Rock tends to breaks or separate, readily along bedding planes.

Bedrock - Any solid rock exposed at the Earth's surface or overlain by unconsolidated material.

Block fault Mountain - A linear mountain that is bounded on both sides by normal faults.

Bottom Set Bed - Layer of fine sediment deposited in a body of standing water beyond the edge of a growing delta and which is eventually built over by the advancing delta. Similarly bottom set beds may accumulate in the wind shadow of a sand dune and be preserved beneath it as the dune advances.

Boundary -The tectonic region in which two plates meet.

Breccia - A clastic rock in which the gravel-sized particles are angular in shape and make up an appreciable volume of the rock.

Brittle - Structural behavior in which a material deforms permanently by fracturing.

Burial metamorphism - Takes place in an environment where pressure and temperature are barely more intense than during diagenesis, typically in a deepening sequence of sediments.

Carbonate rock - A rock consisting primarily of a carbonate mineral such as calcite or dolomite, the chief minerals in limestone and dolostone, respectively.

Cenozoic - The current geologic era, this began 66.4 million years ago and continues to the present.

Chemical sediment - Sediment formed by chemical precipitation from water.

Cirque - A steep-walled hollow in a mountain side, shaped like an amphitheater, or bowl, with one side partially cut away. Place of origin of a mountain glacier.

Clastic - Refers to rock or sediments made up primarily of broken fragments of pre-existing rocks or minerals.

Clay - The name for a family of finely-crystalline sheet silicate minerals.

Cleavage of a mineral - The tendency of a mineral to split along planes determined by the crystal structure.

Col - Mountain pass formed by enlargement of two opposing cirques until their head walls meet and are broken down.

Columnar jointing - The type of jointing that breaks rock, typically basalt, into columnar prisms. Usually the joints form a more or less distinct hexagonal pattern.

Compaction - Reduction of pore space between individual particles as the result of overlying sediments or of tectonic movements.

Compression - Squeezing a material from opposite directions.

Conglomerate - A clastic sedimentary rock composed of lithified beds of rounded gravel mixed with sand.

Contact metamorphism - Metamorphism genetically related to the intrusion (or extrusion) of magmas and taking place in rocks at or near their contact with a body of igneous rock.

Continental arc - A belt of volcanic mountains on the continental mainland that lie above a subduction zone.

Continental crust - The part of the crust that directly underlies the continents and continental shelves. Averages about 35 km in thickness, but may be over 70 km thick under largest mountain ranges.

Continental Divide - The watershed of North America comprising the line of highest points of land separating the waters flowing W from those flowing N or E, coinciding with various ranges of the Rockies, & extending SSE from NW Canada to NW S. America .

Continental ice glacier - An ice sheet that obscures all but the highest peaks of a large part of a continent.

Convergent boundary - A boundary between two plates of the Earth's crust that are pushing together.

Core Innermost zone of Earth - Consists of two parts, an outer liquid section and an inner solid section, both chiefly of iron and nickel with about 10 percent lighter elements. It is surrounded by the mantle.

Craton - The stable portions of the continents that have escaped orogenic activity for the last 2 billion years. Made predominantly of granite and metamorphic rocks.

Crevasse - Deep crevice or open fracture in glacier ice.

Cross-bedding - Bedding laid down at an angle to the horizontal, as in many sand dunes.

Cross-cutting relationships - Geologic discontinuities that suggest relative ages: A geologic feature is younger than the feature it cuts. Thus, a fault cutting across a rock is younger than the rock.

Crust - The upper part of the lithosphere , divided into oceanic crust and continental crust.

Crystal - The multi-sided form of a mineral, bounded by planar growth surfaces, that is the outward expression of the ordered arrangement of atoms within it.

Crystalline - Having a crystal structure.

Cumulate - An igneous rock that forms by crystal settling.

Current ripple mark - An asymmetric ripple mark formed by wind or water moving generally in one direction. Steep face of ripple faces in direction of current. compare oscillation ripple mark.

Debris flow - Fast-moving, turbulent mass movement with a high content of both water and rock debris. The more rapid debris flows rival the speed of rock slides.

Decomposition (chemical weathering) - Weathering processes that are the result of chemical reactions.

Deflation - A process of erosion in which wind carries off particles of dust and sand.

Dehydration - Any process by which water bound within a solid material is released.

Depositional environment - The nature of the environment in which sediments are laid down. They are immensely varied and may range from the deep ocean to the coral reef and the glacial lake of the high mountains. The nature of the depositional environment may be deduced from the nature of the sediments and rock deposited there.

Diagenesis - All the physical, chemical, and biologic changes undergone by sediments from the time of their initial deposition, through their conversion to solid rock, and subsequently to the brink of metamorphism.

Differential weathering - Weathering that occurs at different rates, as the result of variations in composition and mechanical resistance of rocks, or differences in the intensity of weathering processes.

Dike - A tabular igneous intrusion that cuts across the surrounding rock.

Dip - The angle that a structural surface such as a bedding plane or fault surface makes with the horizontal, measured perpendicular to the strike and in the vertical plane.

Dip slip fault - A fault on which the movement is parallel to the dip of the fault plane.

Discharge - In a stream, the volume of water passing through a channel in a given time.

Disconformity - An unconformity in which the beds above the unconformity are parallel to the beds below the unconformity.

Discordant - Cutting across surrounding strata.

Disintegration (mechanical weathering) - The processes of weathering by which physical actions such as frost wedging break down a rock into fragments, involving no chemical change.

Dissolution - A chemical reaction in which a solid material is dispersed as ions in a liquid.

Divergent boundary - Boundary between two crustal plates that are pulling apart.

Dome - An uplift or anticlinal structure, roughly circular in its outcrop exposure, in which beds dip gently away from the center in all directions.

Drag fold - A minor fold produced within a weak bed or adjacent to a fault by the movement of surrounding rocks in opposite directions.

Drainage basin - The area from which a stream and its tributaries receives its water.

Drainage divide - The line that separates one drainage basin from another.

Drift - Glacial deposits laid down directly by glaciers or laid down in lakes, ocean, or streams as result of glacial activity.

Drumlin - Streamlined hill, largely of till, with blunt end pointing into direction from which ice moved. Occur in clusters called drumlin fields.

Ductile - Structural behavior in which a material deforms permanently without fracturing.

Earthflow - A form of slow, but perceptible, mass movement, with high content of water and rock debris.

Elastic - Non-permanent structural deformation during which the amount of deformation (strain) is proportional to the stress.

Elastic rebound - The statement that movement along a fault is the result of an abrupt release of a progressively increasing elastic strain between the rocks on either side of the fault.

Elasticity - The tendency for a body to return to its original shape and size when a stress is removed.

Eon - The primary division of geologic time which are, from oldest to youngest, the Hadean, Archean, Proterozoic, and Phanerozoic eons.

Epoch - A division of geologic time next shorter than a period. Example: the Pleistocene epoch is in the Quaternary period.

Equilibrium line - On a glacier the line separating the zone of accumulation from the zone of ablation.

Era - A division of geologic time next smaller than the eon and larger than a period. Example: The Paleozoic era is in the Phanerozoic eon and includes, among others, the Devonian period.

Erratic - A stone or boulder, glacially transported from place of origin and left in an area of different bedrock composition.

Esker - A winding ridge of stratified drift . Forms in a glacial tunnel and, when ice melts, stands as ridge up to 15 m high and kilometers in length.

Evaporite - A mineral or rock deposited directly from a solution (commonly seawater) during evaporation. For example, gypsum and halite are evaporite minerals.

Exfoliation - The process by which concentric scales, plates, or shells of rock are stripped or spall from the bare surface of a large rock mass.

Exfoliation dome - A large dome-shaped form that develops in homogeneous crystalline rocks as the result of exfoliation.

Extrusive - Pertaining to igneous rocks or features formed from lava released on the Earth's surface.

Fault - The surface of rock rupture along which there has been differential movement of the rock on either side.

Foliation - A planar structure that develops in metamorphic rocks as a result of directed pressure.

Fold and thrust mountains - Mountains, characterized by extensive folding and thrust faulting, that form at convergent plate boundaries on continents.

Foot wall block - The body of rock that lies below an inclined fault plane. compare hanging wall block.

Fossil - Evidence in rock of the presence of past life, such as a dinosaur bone, an ancient clam shell, or the footprint of a long-extinct animal.

Fractional crystallization - A sequence of crystallization from magma in which the early-formed crystals are prevented from reacting with the remaining magma, resulting in a magma with an evolving chemical composition.

Frost wedging - A type of disintegration in which jointed rock is forced apart by the expansion of water as it freezes in fractures.

Geologic column - The arrangement of rock units in the proper chronological order from youngest to oldest.

Geologic time scale - The chronological sequence of units of Earth time.

Glaciation - The formation, advance and retreat of glaciers and the results of these activities.

Glacier - A mass of ice, formed by the recrystallization of snow, that flows forward, or has flowed at some time in the past.

Glacier ice - Ice with interlocking crystals that makes up the bulk of a glacier.

Gneiss - A coarse, foliated metamorphic rock in which bands of granular minerals (commonly quartz and feldspars) alternate with bands of flaky or elongate minerals (e.g., micas, pyroxenes). Generally less than 50% of the minerals are aligned in a parallel orientation.

Gondwana - The southern portion of the late Paleozoic supercontinent known as Pangea. It means, literally "Land of the Gonds" (a people of the Indian subcontinent). The variant Gondwanaland found in some books, therefore, is a tautology.

Graded bedding - Type of bedding sedimentary deposits in which individual beds become finer from bottom to top.

Gradient - Slope of a stream bed or hillside. The vertical distance of descent over horizontal distance of slope.

Granite - Light colored, coarse grained, intrusive igneous rock characterized by the minerals orthoclase and quartz with lesser amounts of plagioclase feldspar and iron-magnesium minerals. Underlies large sections of the continents.

Granitic belt - A region of granitic rock, one of two characteristic regions within cratons.

Ground moraine - Till deposited from main body of glacier during ablation.

Hanging valley - A valley whose mouth is high above the floor of the main valley to which it is tributary. Usually, but not always, the result of mountain glaciation.

Hanging wall block - The body of rock that lies above an inclined fault plane.

Hardness - Resistance of a mineral to scratching, determined on a comparative basis by the Mohs scale.

Hinge fault - A fault along which there is increasing offset or separation along the strike of the fault plane, from an initial point of no separation.

Horn - The sharp spire of rock formed as glaciers in several cirques erode into a central mountain peak.

Ice sheet - A broad, mound-like mass of glacier ice that usually spreads radially outward from a central zone.

Ice shelf - A floating ice sheet extending across water from a land-based glacier.

Icecap - A small ice sheet.

Igneous rock - A rock that has crystallized from a molten state.

Inclined fold - A fold whose axial plane is inclined from the vertical, but in which the steeper of the two limbs is not overturned. compare overturned fold.

Inclusion (xenolith) - A fragment of older rock caught up in an igneous rock.

Index fossil - A fossil that identifies and dates the strata in which it is typically found. To be most useful, an index fossil must have broad, even worldwide distribution and must be restricted to a narrow stratigraphic range.

Index mineral - A mineral formed under a particular set of temperature and pressure conditions, thus characterizing a particular degree of metamorphism.

Inner core - The solid innermost part of the core with a diameter of a little over 1,200 km.

Interlobate moraine - Ridge formed along junction of adjacent glacier lobes.

Intrusive - Pertaining to igneous rocks formed by the emplacement of magma in pre-existing rock.

Island arc - A curved belt of volcanic islands lying above a subduction zone. compare continental arc.

Isoclinal fold - A fold in which the limbs are parallel.

Isostasy - The condition of equilibrium, comparable to floating, of units of the lithosphere above the asthenosphere.

Joint - A surface of fracture in a rock, without displacement parallel to the fracture.

Kettle - Depression in ground surface formed by the melting of a block of glacier ice buried or partially buried by drift.

Lahar - A mudflow composed chiefly of pyroclastic material on the flanks of a volcano.

Laminar flow - Fluid flow in which flow lines are distinct, and parallel and do not mix.

Lateral moraine - Moraine formed by valley glaciers along valley sides.

Laurasia - The northern portion of the late Paleozoic supercontinent called Pangea.

Lava dome - A steep-sided rounded extrusion of highly viscous lava squeezed out from a volcano and forming a dome-shaped or bulbous mass above and around the volcanic vent. The structure generally develops inside a volcanic crater.

Limestone - A sedimentary rock composed mostly of the mineral calcite, CaCO3.

Lineation - A general term applying to any linear feature in a metamorphic rock.

Liquefaction - The transformation of a soil from a solid to a liquid state as the result of increased pore pressure.

Lithification - The process by which an unconsolidated deposit of sediments is converted in to solid rock.

Lithosphere - The rigid outer shell of the Earth. It includes the crust and uppermost mantle and is on the order of 100 km in thickness.

Load - Of a stream, the amount that it carries at any one time.

Luster - The manner in which light reflects from the surface of a mineral, described by its quality and intensity.

Mafic - Referring to a generally dark-colored igneous rock with significant amounts of one or more ferromagnesian minerals, or to a magma with significant amounts of iron and magnesium.

Magma - Molten rock, containing dissolved gases and suspended solid particles. At the Earth's surface, magma is known as lava.

Mantle - That portion of the Earth below the crust and reaching to about 2,780 km, where a transition zone of about 100 km thickness separates it from the core.

Mantle plume - A hypothetical column of hot, partially molten material that rises from an indeterminate depth in the mantle and is thought by some geologists to provide a driving force for plate movement. compare hot spot.

Marble - A metamorphic rock composed largely of calcite. The metamorphic equivalent of limestone.

Margin - The tectonic region that lies at the edge of a continent, whether it coincides with a plate boundary or not.

Medial moraine - Formed by the merging of lateral moraines as two valley glaciers join.

Mesosphere - A zone in the Earth between 400 and 670 km below the surface separating the upper mantle from the lower mantle.

Mesozoic - An era of time during the Phanerozoic eon lasting from 245 million years ago to 66.4 million ago.

Metamorphic rock - A rock changed from its original form and/or composition by heat, pressure, or chemically active fluids, or some combination of them.

Metamorphic zone - A mappable region in which rocks have been metamorphosed to the same degree, as evidenced by the similarity of mineral assemblages in them.

Metamorphism - The processes of recrystallization, textural and mineralogical change that take place in the solid state under conditions beyond those normally encountered during diagenesis.

Monocline - A simple fold, described as a local steepening in strata with an otherwise uniform dip.

Moraine - Landform made largely of glacier till.

Mountain glacier - see valley glacier.

Mudflow - Form of mass movement similar to a debris flow but containing less rock material.

Nonclastic - A term applied to sedimentary rocks that are not composed of fragments of pre-existing rocks or minerals. The term “crystalline” is more commonly used.

Nonconformity - An unconformity that separates profoundly different rock types, such as sedimentary rocks from metamorphic rocks.

Normal fault - A dip-slip fault on which the hanging wall block is offset downward relative to the foot wall block. compare reverse fault.

Oceanic crust - That part of the crust underlying the ocean basins. Composed of basalt and having a thickness of about 5 km.

Original horizontality - Refers to the condition of beds or strata as being horizontal or nearly horizontal when first formed.

Orogeny - The process of mountain building.

Oscillation ripple mark - A symmetric ripple mark formed by waves, which move water back and forth. compare current ripple mark.

Outer core - The outermost part of the core. It is liquid, about 1,700 km thick, and separated from the inner, solid core by a transition zone about 565 km thick.

Outwash - Beds of sand and gravel laid down by glacial melt water .

Overturned fold - An inclined fold in which one limb has been tilted beyond the vertical, so that the stratigraphic sequence within it is reversed. compare inclined fold.

Paleozoic - An era of geologic time lasting from 570 to 245 million years ago.

Pangea - A supercontinent that existed from about 300 to 200 million years ago, and included most of the continental crust of the Earth.

Pegmatite - An extremely coarse-grained igneous rock with interlocking crystals, usually with a bulk chemical composition similar to granite but commonly containing rare minerals enriched in lithium, boron, fluorine, niobium, and other scarce metals.

Period - In the geologic time scale a unit of time less than an era and greater than an epoch. Example: The Tertiary period was the earliest period in the Cenozoic era and included, among others, the Eocene epoch.

Phaneritic - A textural term meaning "coarse-grained" that applies to igneous rocks.

Phanerozoic - The most recent eon of geologic time beginning 570 million years ago and continuing to the present.

Phenocryst - Any relatively large, conspicuous crystal in a porphyritic igneous rock.

Piedmont glacier - A glacier that spreads out at the foot of mountains, formed by the coalescence of two or more valley glaciers.

Plate - A rigid segment of the Earth’s lithosphere that moves horizontally and adjoins other plates along zones of seismic activity. Plates may include portions of both continents and ocean basins. Plate boundaries The zones of seismic activity long which plates are in contact. These may coincide with continental margins, but usually do not. Movement between plates is predominately horizontal, and may be divergent, or convergent, or side-by-side.

Plate tectonics - A theory of global tectonics according to which the lithosphere is divided into mobile plates. The entire lithosphere is in motion, not simply those segments composed of continental material. compare continental drift.

Plucking (quarrying) - A process of erosion in which the glacier pulls loose pieces of bed rock.

Plume - The movement of water along flow lines from a point source of ground water pollution toward its eventual emergence at the surface.

Plunging fold - A fold in which the axis is inclined at an angle from the horizontal.

Pluton - An igneous intrusion. Porphyritic A texture of an igneous rock in which large crystals (phenocrysts) are set in a matrix of relatively finer-grained crystals or of glass.

Precambrian - An informal term to include all geologic time from the beginning of the Earth to the beginning of the Cambrian period 570 million years ago.

Proterozoic - The geologic eon lying between the Archean and Phanerozoic eons, beginning about 2.5 billion years ago and ending about 0.57 billion years ago.

Pyroclastic - Pertaining to clastic material formed by volcanic explosion or aerial expulsion from a volcanic vent.

Rain shadow - formed by blocking moisture-bearing winds with mountain barriers.

Recessional moraine - Ridges of glacial till marking halt and slight readvance of glacier during its general retreat.

Regional metamorphism - Metamorphism affecting an extensive region, associated with orogeny.

Relative time - Dating of rocks and geologic events by their positions in chronological order without reference to number of years before the present.

Reverse fault - A dip-slip fault on which the hanging wall block is offset upward relative to the foot wall block. Compare normal fault.

Rhyolite - A fine-grained silica-rich igneous rock, the extrusive equivalent of granite.

Rift (graben) - A valley caused by extension of the Earth's crust. Its floor forms as a portion of the crust moves downward along normal faults.

Rio Grande Rift - The Rio Grande Rift is a rift valley extending north from Mexico, near El Paso, Texas through New Mexico into central Colorado, and is part of the Basin and Range Province.

Rock cycle - The concept of a sequence of events involving the formation, alteration, destruction and reformation of rocks as a result of geologic processes and which is recurrent, returning to a starting point. It represents a closed system. compare rock system.

Rock flour - Finely divided rock material ground by glacial action and fed by streams fed by melting glaciers.

Rock glacier - A mass of ice-cemented rock rubble found on slopes of some high mountains. Movement is slow, averaging 30 to 40 cm/yr.

Sandstone - A clastic sedimentary rock in which the particles are dominantly of sand size, from 0.062 mm to 2 mm in diameter.

Schist - A strongly foliated, coarsely crystalline metamorphic rock, produced during regional metamorphism, that can readily be split into slabs or flakes because more than 50% of its mineral grains are parallel to each other.

Schistosity - The foliation in a schist, due largely to the parallel orientation of micas.

Seafloor spreading - Process by which ocean floors spread laterally from crests of main ocean ridges. As material moves laterally from the ridge, new material replaces it along the ridge crest by welling upward from the mantle. compare continental drift, plate tectonics.

Seamount (guyot) - A volcanic mountain on the seafloor. If flat-topped, it is a guyot.

Sedimentary rock - Rock formed from the accumulation of sediment, which may consist of fragments and mineral grains of varying sizes from pre-existing rocks, remains or products of animals and plants, the products of chemical action, or mixtures of these.

Shale - A mudstone that splits or fractures readily.

Shatter cone - A distinctively striated conical structure in rock, ranging from a few centimeters to a few meters in length, believed to have been formed by the passage of a shock wave following meteorite impact.

Shear - Rock deformation involving movement past each other of adjacent parts of the rock and parallel to the plane separating them.

Shear strength - The resistance of a body to shear stress.

Shear stress - The stress on an object operating parallel to the slope on which it lies.

Sheeting - A type of jointing produced by pressure release (unloading) or exfoliation.

Silica - Silicon dioxide (SiO2) as a pure crystalline substance makes up quartz.

Sill - A tabular igneous intrusion that parallels the planar structure of the surrounding rock.

Slaty cleavage - A style of foliation common in metamorphosed mudstones, characterized by nearly flat, sheet-like planes of breakage, similar in appearance to a deck of playing cards. compare cleavage.

Slickenside - A polished and smoothly striated surface that results from friction along a fault plane.

Sorting - The range of particle sizes in a sedimentary deposit. A deposit with a narrow range of particle sizes is termed "well-sorted."

Stratification - The accumulation of material in layers or beds.

Stratified drift - Debris washed from a glacier and laid down in well-defined layers.

Stratigraphy - The succession and age relation of layered rocks.

Striations - Scratches, or small channels, gouged by glacier action. Occur on boulders, pebbles, and bedrock. Striations along bedrock indicate direction of ice movement.

Strike - The compass direction of the intersection between a structural surface (e.g., a bedding plane or a fault surface) and the horizontal.

Strike-slip fault (transcurrent fault) - A fault on which the movement is parallel to the fault's strike.

Subduction zone - A narrow, elongate region in which one lithospheric plate descends relative to another.

Surging glacier - A glacier that moves rapidly (tens of meters per day) as it breaks away from the ground surface on which it rests.

Syncline - A fold that is convex downward, or that had such an attitude at some stage in its development.

Talus - A slope built up by the accumulation of rock waste at the foot of a cliff or ridge.

Tarn - A lake in the bedrock basin of a cirque.

Temperate glacier - A glacier whose temperature throughout is at, or close to, the pressure point of ice, except in winter when it is frozen for a few meters below the surface.

Tensile fracture - A fracture caused by tensional stress in a rock.

Tension - A stress that tends to pull a body apart.

Tephra - A general term for all pyroclastic material.

Terminal moraine (end moraine) - Ridge of till marking farthest extent of glacier.

Thrust fault - A reverse fault on which the dip angle of the fault plane is 15 degrees or less.

Till (unstratified drift) - Glacial drift composed of rock fragments that range from clay to boulder size and randomly arranged without bedding.

Transform boundary - A plate boundary in which plates on opposite sides of the boundary move past each other in opposite directions.

Transform fault - A plate boundary that ideally shows pure strike-slip movement. Associated with the offset segments of midocean ridges.

U-shaped valley - A valley carved by glacier erosion and whose cross-valley profile has steep sides and a nearly flat floor, suggestive of a large letter "U".

Unconformity - A buried erosion surface separating two rock masses.

Uniformitarianism - Principle acknowledges that past processes, even if the same as today, may have operated at different rates and with different intensities than those of the present.

Valley glacier (alpine glacier, mountain glacier) - Streams of ice that flow down valleys in mountainous areas.

Viscosity - The internal resistance to flow in a liquid.

Volcanic ash - The dust-sized, sharp-edged, glassy particles resulting from an explosive volcanic eruption.

Weathering - The process by which Earth materials change when exposed to conditions at or near the Earth's surface and different from the ones under which they formed. compare decomposition , disintegration.

Welded tuff - A pyroclastic rock in which glassy clasts have been fused by the combination of the heat retained by the clasts, the weight of overlying material, and hot gases.

Zone of accumulation - The area in which ice accumulates in a glacier.

Zone of fracture - The near surface zone in a glacier that behaves like a brittle substance.

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Appendix
Geologic Time Scale

Geologic time is divided into a four-level hierarchy of time intervals:

-EONS -- The first and largest division of geologic time.
-ERAS -- The second division of geologic time; each era has at least two periods.
-PERIODS-- The third division of geologic time. Periods are named for either location or characteristics of the defining rock formations.
-EPOCHS -- The fourth division of geologic time; represents the subdivisions of a period.

The time of the transition from one interval of geologic time to the subsequent one is usually marked by a relatively abrupt change in fossil types and numbers.

Era	Period	(millions of years ago)	Major Geologic Events
Cenozoic	Quaternary	Present-1.8	Ice Ages Major canyon-cutting
	Tertiary	1.8-65	Large volcanic eruptions Laramide Orogeny: uplift and mountain-building
Mesozoic	Cretaceous	65-144	Dinosaurs died Interior Seaway Swamp conditions Coals and shales deposited
	Jurassic	144-206	Desert conditions Submergence and salt flats
	Triassic	206-248	Dinosaurs roamed
Paleozoic	Permian	248-290	Ancestral Rockies almost entirely eroded away
	Pennsylvanian	290-323	Uplift of Ancestral Rockies Erosion of older rocks and redeposition as sediments
	Mississippian	323-354	
	Devonian	354-417	Widespread shallow seas
	Silurian	417-443	Periods of erosion
	Ordovician	443-490	
	Cambrian	490-543	
Precambrian	Accounts for more than 85% of geologic time	543-3,800?	Major igneous intrusions and metamorphism

→ 30,000-11,000 years ago - Pinedale Glaciers

300,000-127,000 years ago - Bull Lake Glaciers

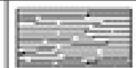
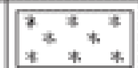
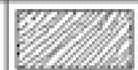
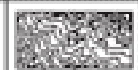
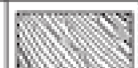
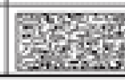
→ 65 Ma – 28 Ma Laramide Mountain Building

→ 285 Ma – Ancestral Rockies Mountain Building

→ 1700 Ma – Precambrian Mountain Building

Figure 3: NPS

Scheme for Metamorphic Rock Identification

TEXTURE		GRAIN SIZE	COMPOSITION	TYPE OF METAMORPHISM	COMMENTS	ROCK NAME	MAP SYMBOL
FOLIATED	MINERAL ALIGNMENT	Fine	MICA	Regional	Low-grade metamorphism of shale	Slate	
		Fine to medium	MICA, QUARTZ, FELDSPAR, AMPHIBOLE, GARNET	(Heat and pressure increase with depth)	Foliation surfaces shiny from microscopic mica crystals	Phyllite	
					Platy mica crystals visible from metamorphism of clay or feldspars	Schist	
	BAND-ING	Medium to coarse	MICA, QUARTZ, FELDSPAR, AMPHIBOLE, GARNET, PYROXENE		High-grade metamorphism; some mica changed to feldspar; segregated by mineral type into bands	Gneiss	
NONFOLIATED		Fine	Variable	Contact (Heat)	Various rocks changed by heat from nearby magma/lava	Hornfels	
		Fine to coarse	Quartz	Regional or Contact	Metamorphism of quartz sandstone	Quartzite	
			Calcite and/or dolomite		Metamorphism of limestone or dolostone	Marble	
		Coarse	Various minerals in particles and matrix		Pebbles may be distorted or stretched	Metaconglomerate	

Scheme for Sedimentary Rock Identification

INORGANIC LAND-DERIVED SEDIMENTARY ROCKS					
TEXTURE	GRAIN SIZE	COMPOSITION	COMMENTS	ROCK NAME	MAP SYMBOL
Clastic (fragmental)	Pebbles, cobbles, and/or boulders embedded in sand, silt, and/or clay	Mostly quartz, feldspar, and clay minerals; may contain fragments of other rocks and minerals	Rounded fragments	Conglomerate	
			Angular fragments	Breccia	
	Sand (0.2 to 0.006 cm)		Fine to coarse	Sandstone	
	Silt (0.006 to 0.0004 cm)		Very fine grain	Siltstone	
	Clay (less than 0.0004 cm)		Compact; may split easily	Shale	
CHEMICALLY AND/OR ORGANICALLY FORMED SEDIMENTARY ROCKS					
TEXTURE	GRAIN SIZE	COMPOSITION	COMMENTS	ROCK NAME	MAP SYMBOL
Crystalline	Varied	Halite	Crystals from chemical precipitates and evaporites	Rock Salt	
	Varied	Gypsum		Rock Gypsum	
	Varied	Dolomite		Dolostone	
Bioclastic	Microscopic to coarse	Calcite	Cemented shell fragments or precipitates of biologic origin	Limestone	
	Varied	Carbon	From plant remains	Coal	

INTERVALS OF TIME: ERA	PERIOD	MILLIONS OF YEARS AGO	FORMATION	THICKNESS (FEET)	DESCRIPTION	WEATHERING CHARACTERISTICS
CENOZOIC	QUATERNARY	2	NOT NAMED	0-25	GRAVEL, SAND, SILT	LOOSE
	TERTIARY	70				
MESOZOIC	CRETACEOUS	135	LARAMIE, FOX HILLS, PIERRE, NIOBRARA, BENTON, DAKOTA	10,400	GRAY TO TAN SHALES, SANDSTONES, LIMESTONES, FOSSILS	SANDSTONES STAND ON RIDGES, SHALE FORMS SLOPES
	JURASSIC	180	MORRISON	300	SHALE TO SANDSTONE	FORMS SLOPES
			ENTRADA	30	CROSS-BEDDED SANDSTONE	RESISTANT
	TRIASSIC	225				
PALEOZOIC	PERMIAN	270	LYKINS	675	RED SHALE, SILTSTONE, SANDSTONE	SOFT. VALLEYS AND SLOPES
			LYONS	220	PINK SANDSTONE	HARD RIDGES
	PENNSYLVANIAN	305	FOUNTAIN	800	RED SANDSTONES AND CONGLOMERATE	LOCALLY HARD RIDGES
	MISSISSIPPIAN	350				
	DEVONIAN	400				
	SILURIAN	420				
	ORDOVCIAN	500				
	CAMBRIAN	600				
PRECAMBRIAN		1700	IDAHO SPRINGS FM., BOULDER CREEK GR.	UNKNOWN	METAMORPHIC & IGNEOUS ROCKS	CRYSTALLINE, HARD

APPROXIMATE AGE OF THE EARTH = 4.6 BILLION YEARS

Geologic and Stratigraphic Column for the Boulder Area (Based on Runnells, 1976)