From The Bottom Of The Ocean To The Top Of The World (…and Everything in Between):

The Geology of Pagosa Country

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Introduction

Pagosa Country existed long before humans began carving up the land into political territories. It is roughly that area of Colorado south of the Continental Divide, west of the Navajo River, north of Chama, New Mexico, and east of the Piedra River and Chimney Rock. Of course, local experts may prefer other dividing lines, but Pagosa Country is broadly united by a complex and dramatic geologic past that built this land we live in and love.

Pagosa Country has existed as long as the Earth, so in that respect its beginnings are no different that those of our home planet. As with all parts of the surface of the Earth, Pagosa Country began as a stretch of molten rock, battered by meteorites and small planetoids, blasted by the intense radiation of the young Sun, and stirred by the tides of the brand-new Moon. Nothing remains of those days, however. The oldest rocks now known on Earth date back to 4.2 billion years, and those of the Moon come close to 4.5 billion years, almost at the start of our planetary system at 4.6 billion.

Pagosa Country's oldest rocks, exposed among the heights of the Continental Divide in the San Juan Mountains and in the deepest part of the upper Piedra River Canyon, date back to about 1.8 billion years, not quite halfway to the start of it all. From there forward, the rock record is spotty- much of it is missing, either because rocks were never deposited in some eras, or because later erosion stripped away the older rocks and the history they contained. Much of the earliest record of Pagosa Country now rests in the bottom of the San Juan Basin in Northern New Mexico, ground away by glaciers and floods and carried south by our never-resting rivers.

This is primarily an effort to interpret the history of Pagosa Country through understanding of its geologic record. Some of the included material is scientific, and there are references to papers and reports of the many researchers who work to unravel the hidden secrets of the rocks. Other parts are more interpretive and speculative, drawing conclusions from the known geologic evidence. This compilation contains several different formats: text documents, PowerPoint presentations, geologic road logs, and images.

Pagosa Country Geologic History: *the Text*

Pagosa Country (the Town of Pagosa Springs and this part of Archuleta, Hinsdale, Mineral and Conejos Counties) lies between two major geologic terrains, or provinces: the mountains of the San Juan Volcanic Field to the north and east, and the San Juan Basin sedimentary depression to the south and west. Both the mountains and the basin have influenced the local geology and landforms, creating the major structures of this area; however, erosion caused by glaciers and running water has sculpted and softened the land since the inland sea drained away and the last of the gigantic volcanos exploded.

The following summary is adapted from "Mineral Resource Potential and Geology of the San Juan National Forest, Colorado" (Van Loenen, Gibbons, Dersch & Raby, 1994, USDA Forest Service Administrative Report, Denver, Colorado). The San Juan National Forest, part of the larger area of public lands in the southwestern part of Colorado, contains about 2.1 million acres of chiefly mountainous terrain that stretches for nearly 120 miles from east to west and 45 miles north to south. It lies southwest of the Continental Divide, and all drainage from the Forest is into the Colorado River system. The Forest rises from about 6,000 feet in elevation in the canyonlands of the southern and western margins, up to the spectacular heights of the Divide, over 13,000 feet in elevation. Mountains and ranges of the region include the Needle, San Miguel, La Plata, and San Juan; these are generally lumped together as the San Juan Mountains. Bounding Pagosa Country, these mountains are the remnants of titanic volcanoes, identified by geologists as the San Juan Volcanic Field. Pagosa Country lies along the southern edge of the eastern San Juans, between the Piedra River to the west and the Navajo River to the east, stretching down to about the Colorado-New Mexico state line. Elevations range from about 6,000 feet to over 12,000 feet.

The rocks exposed in the Forest represent a suite of sedimentary, plutonic and volcanic rocks that accumulated over a time span of nearly 1.8 billion years. The oldest rocks, Proterozoic (over 2 billion years) in age, are exposed in the needle Mountains in the central region of the Forest. These ancient rocks are flanked on the north and east by Tertiary (40 to 10 million years) volcanics, and on the south and west by Paleozoic and younger (400 to 20 million years) sedimentary rocks that were laid down in the ancient depressions now known as the Paradox and San Juan Basins. Major rivers and streams, assisted by intense glacial erosion, have cut deep canyons throughout much of the Forest, creating the landscape seen today. This action has been particularly important in the shaping of Pagosa Country; the gigantic volcanoes that created the San Juan Mountains to our north have been sculpted by ice and smoothed by floods from melting glaciers.

The geologic framework of the San Juan National Forest results from a long and complex history of faulting and uplift, basin development, sedimentation, plutonism, and volcanism. The broad stages of development of the area are:

1. deposition of sedimentary rocks that were later metamorphosed and still later intruded by a succession of igneous rocks (plutons) from 1.7 to about 1.4 billion eyars ago;
2. a gap in the rock record for 900 million years due to erosion or nondeposition of rocks;
3. alternation of deposition of clastic and carbonate rocks with minor local uplift and erosion between about 550 million and 320 million years ago;
4. the first cycle of uplift of the Uncompahgre-San Luis Highlands, an element of the Ancestral Rocky Mountains, beginning about 320 million years ago;
5. intense erosion of the uplift and deposition of "redbeds" and other continental clastic sediments from 365 million to about 140 million years ago, sending pulses of sediment into Pagosa Country and laying down the oldest rocks exposed below the Continental Divide today (about 290 million years old);

6 deposition of sediment in and adjacent to the great Cretaceous age seas that covered the area intermittently from 140 million to about 70 million years ago, building the Mancos Shale which is today's bedrock for the town of Pagosa Springs, the Dakota Sandstone which floors Pagosa Lakes, and the Lewis Shale, the gray and black hills covering much of Pagosa Country;

7 renewed uplift resulting from compressional forces during the Larimide Orogeny (mountain-building), accompanied by intrusion of ore-related plutons about 70 to 65 million years ago;

8 massive volcanism beginning about 40 million years ago and continuing to about 20 million years ago, accompanied by ore-related igneous intrusions and possibly the largest volcanic caldera eruption ever to be documented on Earth, stretching north from Pagosa Country to near Alamosa, Colorado; and

9 a final pulse of ore-related igneous intrusive activity during the period from 10 to 5 million years ago, followed by fluvial and glacial processes that formed the present-day landscape, with the residual heat of the cooling igneous plutons still feuling hot springs across the area including the Great Pagosa Hot Springs.

This complex geologic history has blessed the region with incomparable beauty and valuable natural resources of water, forests, diverse wildlife habitat, and mineral and energy reserves. The first Pagosans, American Indians migrating from the north, were drawn to the area some 12,000 years ago, possibly folloing migrating animal herds and using the hot springs, and they were followed by waves of colonists, adventurers, settlers, developers and finally, today's recreationists. All these people's livelihoods and pastimes are rooted in the complex geology of Pagosa Country.

The following table lists the ages and effects of the most important geologic events that made Pagosa Country what it is today. Where rocks of that age are exposed in this area, their formation names and locations are listed. Not all ages of the Earth are preserved in the rocks- some rock layers were eroded away and destroyed by later geologic events, and some ages did not deposit a layer of stone for us to study. Many important geological events were global in nature; if there is no local evidence of their happening, notes in the table identify where the information comes from. The references provide a list for further study.

The geologic history of our Earth is immensely long- 4.6 billion years, the current best estimate of the planet's age, is hard to express in human terms. The oldest local rocks are less than half the Earth's age. The most influential events that shaped the modern landscape here, the opening of the massive crack in the continent we call the Rio Grande Rift and the explosion of the La Garita Caldera at its northern end, occurred "only" about 29 million years ago. The glaciers that carved the mountains and the floods that scoured the river valleys ended less than 15,000 years ago- in geologic terms, just yesterday.

What about the future? There's no way to know precisely. But some things can be expected to continue, as they have occurred in the past. The Colorado Plateau is still rising, taking us with it, and the San Juan River will continue to cut away at the rising land, deepening its channel and widening its domain. The entire continent is moving west at about 1 inch a year, gradually closing the Pacific Basin and shrinking the ocean. Eventually, some 50 million years from now, Los Angeles will be just off the coast of Alaska and Japan will be rising atop a new mountain range where the ancient Pacific Ocean used to be. Pagosa Country will probably lie in the bottom of a wide, deep valley, surrounded by low rolling hills and broad floodplains. No more mountains, no more dramatic cliffs or waterfalls, no more Continental Divide… we may even be under a new sea, buried by layers of soft, silent mud.

But other possibilities abound. If the Rio Grande Rift becomes active again, Pagosa may once more be the home of gigantic volcanos and a new mountain range. New Ice Ages will almost certainly occur, and glaciers and meltwater will again carve and cut and wash away the land. Meteorites and comets and asteroids will hit the Earth in the future, as they have always done, and no one can predict what will happen on those unlucky days to come.

The only thing that we can predict with certainty is change. The rocks of the earth have a natural cycle, just as living things do, and they cannot remain unchanged. So we must appreciate this landscape as a single snapshot of time in a long and amazingly variable movie. Pagosa has been, over the years, a sea of molten lava seared by ultraviolet energy and corroded by a toxic atmosphere; the bottom of an ocean; a string of volcanic islands in a tropical sea; a temperate beach; a forest of palm trees and ferns; a dead land buried under a mile of ice; a steaming jungle populated by immense dinosaurs; a cold ruin destroyed by an asteroid impact; a wonderland of bubbling hot springs and geysers; a searing salt desert; a wasteland of smoking volcanic ash and blasted, dead forests; a rocky, storm-wracked coastline; and the beautiful, mountain-valley home we know today, commanding views from the Continental Divide at the top of the world. Pagosa Country has been all these things, and more is yet to come.

This table begins at the beginning, at least for our Earth, and tells the scientifically understood story of Pagosa Country's formation and change. Following the table are references for further study. Science is an ongoing and self-correcting process, and, like Pagosa Country itself, the story will change as new information is discovered and new interpretations arise.

A version of this table (TIMELINE.ppt). and the story of the La Garita Caldera eruption (SAN JUAN SUPERVOLCANO.ppt) are included as PowerPoint presentations on this disk.

Pagosa Country Geologic History: *the Table*

This table follows a standard geologic format: starting with the oldest time and proceeding to the most recent.

YEARS AGO	GEOLOGIC TIME	ROCK FORMATIONS & LOCATIONS FOUND	MAJOR GEOLOGIC, ECOLOGIC & CLIMATIC EVENTS AFFECTING PAGOSA SPRINGS AREA
- 4,650 Million (M)	Precambrian Eon (symbol: pC)	No rocks of this age are exposed at the surface of the Earth; dating is from meteorites The Precambrian contains 89% of Earth's history	Formation of the Earth: a molten sphere under constant impact by planetesimals and asteroids; future site of Pagosa is an ocean of magma under a superheated toxic atmosphere
- 4,500 M	pC Early Archean Era	None exposed at the surface; dating is from lunar rocks The Precambrian is subdivided into several eras. Most major divisions in geologic time are based on mass extinctions or other obvious changes in the geologic record	Formation of the Moon by impact of a Mars-size planet with the Earth, creating a ring of debris around the Earth. This condenses into the Moon, at a distance of 30,000 miles above Earth and an orbital period of 6 days (the current distance of the moon is 240,000 miles and its orbital period is 28.29 days). Any solid surface that existed before the impact is destroyed and remelted
- 4,200 M	pC	None exposed in this area; dating is from Australian zircons Standardized colors are commonly used to denote geologic time periods	Earth's crust begins to crystallize into a solid layer. Frequent asteroid impacts disrupt the surface; there is no liquid water and the early atmosphere is toxic
- 4,000 M	pC	None exposed in this area; dating is from Canadian Shield rocks of Great Slave Lake	First nucleus of North American crust forms; asteroids continue to impact Earth; comets add water to the atmosphere, triggering the first significant rainfall; violent storms occur as rainwater floods molten areas. Paogsa area is likely still molten rock
- 3,850 M	pC	None exposed in this area; dating is from Isua, West Greenland	Late Heavy Bombardment Era: high numbers of comets and asteroids impact the Earth; the Sun is 30% less bright than today, but has a higher untraviolet flux. Continents are composed of small econiches, thermal springs, deep fractures, and small shallow seas; water is highly acid; the first evidence of life activity appears in sediments at the shore of the seas
- 3,600 M	pC	None exposed in this area	Asteroid impacts lessen considerably, allowing stable crust to form. The first deep oceans and the earliest granite-greenstone terrains form, as the early continents solidify; massive volcanos erupt huge amounts of gas and debris as Earth's deeper rocks vent their heat to the surface
- 3,400 M	pC Middle Archean Era	None exposed in this area	The Earth's atomsphere is mostly carbon dioxide and nitrogen; oceans cover large parts of the Earth; first ecosystems form as life colonizes the oceans; earliest fossils of living things
- 3,000 M	pC Late Archean Era	None exposed in this area	Cooling of the brittle crust and intrusion of water into the mantle affects melting of the mantle and tectonic activity; continents collide and fuse together, growing larger and creating mountain ranges and deep basins
- 2,700 M	pC	None exposed in this area	Major period of crust formation occurs across the planet; plate tectonics and volcanic activity emplace the major part of Earth's metallic ore deposits; the climate is generally stable and life begins to alter the Earth's atmosphere and ocean chemistry

YEARS AGO	GEOLOGIC TIME	ROCK FORMATIONS & LOCATIONS FOUND	MAJOR GEOLOGIC, ECOLOGIC & CLIMATIC EVENTS AFFECTING PAGOSA SPRINGS AREA
- 2,500 M	pC Early Proterozoic Era	None exposed in this area; dating is from Australia and Africa	A global ice age begins, freezing the entire land surface of the planet and possibly the surface of the oceans, lasting tens of millions of years and seriously affecting life on Earth. Gradual buildup of CO2 from oceanic life and other factors warms the planet and ends the ice age
- 2,200 M	pC	None exposed in this area	First evidence of free oxygen in the atmosphere, generated as a waste product of oceanic life (about 2% of today's oxygen level); oxygen accelerates weathering of rocks and the erosion cycle. The future Pagosa is part of a volcanic island complex called the Mazatzl Province; the climate is hot and humid; the first evidence of life on land may date from this time
- 2,100 M	pC	None exposed in this area	The oceans teem with single-celled life, generating so much waste oxygen (15% of today's level) that it causes toxic ecosystem destruction; most of the anaerobic life forms die out, and modern aerobic (oxygen-dependent) life forms gain dominance
- 2,000 M	pC	Vallecito Conglomerate: north of Bayfield	Pagosa area is a cobble-beach shoreline, with a quiet stable climate, but subject to periodic oceanic storms, similar to Oregon coast today
- 1,900 M	pC	Irving Formation: Weminuche Wilderness Area north of Bayfield	Tectonic activity brings the Pagosa beaches and landmass closer to North America; collision and subduction begins, creating volcanos that erupt large amounts of debris into the narrowing ocean basin
- 1,750 M	pC	Twilight Gneiss: Weminuche Wilderness	The continental collision metamorphoses basalt and dacite lava flows into gneiss as the shallow ocean basin fills and closes. Pagosa joins North America along a northwest-southeast contact zone, creating southwest Colorado as the Mazatzl and Yavapai Provinces collide and compress after bouncing off of Australia, during the formation of the Rodinia Supercontinent
- 1,600 M	pC Middle Proterozoic Era	No fossils are preserved here; dating is from fossils in Canada and Australia	Evolution of cells with nuclei- mostly algae and protozoa, and multicellular life forms- mostly seaweeds. Pagosa is a series of low volcanic mountains near the western shore of North America
- 1,460 M	pC	Eolus Granite, Weminuche Wilderness	Partial melting of the lower crust, probably due to the heat of the continental collision, emplaces granitic plutons throughout the Colorado Plateau region; Pagosa is subject to greatly increased volcanic eruptions and mountain-building
-1,000 M	pC	Eolus Granite	Completion of Rodinia Supercontinent; Pagosa area is located about 40 degrees south of the Equator, with a temperate climate and mountain-valley geography, probably quite similar to today (located today at 37 degrees north latitude)
- 900 M	pC Late Proterozoic Era	None exposed in this area	Global ice age of extreme severity- several cycles lasting together about 200 million years; Pagosa's climate is cold and dry, with deep glacial ice covering everything but the highest peaks
- 650 M	pC	No rocks of this age are exposed in this area	End of planetary deep freeze; explosion of highly complex life forms throughout the world's oceans; many bizarre creatures appear, unlike any life forms today
- 544 M	***Paleozoic Era/Cambrian Period Boundary***		
- 510 M	Symbol: C Paleozoic Era, Cambrian Period	Ignacio Quartzite: Weminuche Wilderness	Gradual spread of a shallow sea eastward across low-lying Precambrian terrain; Pagosa area is broad tidal flats or shallow sea floor

YEARS AGO	GEOLOGIC TIME	ROCK FORMATIONS & LOCATIONS FOUND	MAJOR GEOLOGIC, ECOLOGIC & CLIMATIC EVENTS AFFECTING PAGOSA SPRINGS AREA
- 495 M	***Ordovician Period Boundary***		
- 450 M	Symbol: O Paleozoic Era, Ordovician Period	Ignacio Quartzite	Several periods of uplift and subsidence create a landscape of sea floor, low plains and shorelines
- 442 M	***Silurian Period Boundary***		
- 435 M	Symbol: S Paleozoic Era, Silurian Period	No rocks of this age exposed in this area	Marine extinction; the cause isn't known, but about 20% of all life forms in the sea died out at this time
- 416 M	***Devonian Period Boundary***		
- 400 M	Symbol: D Paleozoic Era, Devonian Period	No rocks of this age exposed in this area	About 100 million years of intense erosion have removed all traces of this time period from the local rock record. Pagosa was probably uplifted into a series of low hills during this time
- 390 M	D	No rocks of this age are exposed in this area	Global ice age begins; Pagosa area has a cold, dry climate
- 370 M	D	No rocks of this age are exposed in this area	Vascular plants have taken over the land by this time, spreading from the seashores and developing stem and leaf tissue to withstand the harsh climate of the land. There is a sharp decline in global atmospheric CO_2 levels about this time
- 367 M	D	No rocks of this age are exposed in this area	1 or 2 comets impact on the shallow sea floor in southeastern Nevada (the Alamo Event), the possible cause of a mass extinction (dated at around 364 million years)
- 360 M	D	Elbert Formation, Ouray Formation: Weminuche Wilderness	The shallow sea advances to the east across highly weathered terrain; Pagosa area is tidal flats and sea floor
- 355 M	D	Elbert Formation	A mass extinction kills about 21% of all sea life; the cause is not known
- 354 M	***Carboniferous/Mississippian Period Boundary***		
- 325 M	Symbol: M Paleozoic Era, Carboniferous or Mississippian Period	Leadville Limestone: Weminuche Wilderness	Pagosa is a quiet sea floor, made up of lime mud flats; the sea retreats to the west, leaving tidal flats and shoreline. A karst (sinkhole) surface forms as limestone weathers
- 323 M	***Carboniferous/Pennsylvanian Period Boundary***		
- 300 M	Symbol: IP Paleozoic Era, Pennsylvanian Period	Molas Formation: Piedra River canyon	The general area subsides, forming another shallow sea basin. Amphibians are the dominant land animal. Toward the end of deposition of the Molas Formation, the area rises; the Paradox Basin forms to the west and the Uncompahgre Uplift raises the Pagosa area and drains the sea
- 295 M	IP	Rico Formation, Hermosa Formation: Piedra River canyon	Uplift of the area continues. Erosion of higher land to the northeast buries the old sea floor and its marine fossils; Paogsa is a region of rivers and swamps
- 295 M	***Permian Period Boundary***		
- 270 M	Symbol: P Paleozoic Era, Permian Period	Cutler Formation: Piedra River canyon	The ancestral Rocky Mountains rise, dumping sediment into the rivers of the Pagosa area. The first conifer trees appear and begin to dominate the forests

YEARS AGO	GEOLOGIC TIME	ROCK FORMATIONS & LOCATIONS FOUND	MAJOR GEOLOGIC, ECOLOGIC & CLIMATIC EVENTS AFFECTING PAGOSA SPRINGS AREA
- 260 M	P	No rocks of this age are exposed in this area	Plate tectonics create the supercontinent of Pangea; the first mammals and reptiles appear about this time and begin to replace amphibians as the dominant land animals
- 248 M	***Mesozoic Era/Triassic Period Boundary***		
- 248 M	Symbol: Tr Mesozoic Era, Triassic Period	No rocks of this age are exposed in this area	The Permian Extinction Event occurs, causing rapid deforestation, extreme chemical weathering, acid rain, massive erosion, and depletion of the atmosphere's oxygen level from 35% down to 13%; about 97% of all life forms on Earth die, resulting in a major restructuring of all Earth's ecosystems. The cause is unknown but massive volcanic eruptions, supercontinent creation, and/or asteroid impacts may be to blame
- 245 M	Tr	No rocks of this age are exposed in this area; dating and estimation of climate effects from Australia	The Early Triassic Greenhouse period begins, causing extremely hot and humid conditions worldwide. Fungi and ferns dominate the land, the only major plant survivors of the Extinction. Over the next 2 million years, the earth recovers and dinosaurs appear. Southwest Colorado is a vast desert region of sand dunes and alkali lakes
- 240 M	Tr	No rocks of this age are exposed here	To the south, the San Juan Basin forms; mountains rise to the north. The first flying and sea-dwelling reptiles appear; dinosaurs dominate the land ecologies, suppressing mammals and reptiles completely
- 230 M	Tr	No rocks of this age are exposed in this area	Southwest Colorado continues to rise. Pagosa becomes an arid region of low hills and plains
- 210 M	Tr	Dolores Formation: Piedra River canyon	The mountains to the northeast erode. Pagosa and the Four Corners are within 10 degrees of the Equator on the western margin of the Pangea Supercontinent, a region of swamps, rivers and lakes, and floodplains with strong seasonal, temperate to subtropical climate; dinosaurs are the major land animal
- 205 M	***Jurassic Period Boundary***		
- 175 M	Symbol: J Mesozoic Era, Jurassic Period	No rocks of this age are exposed in this area	The region lifts, draining the swamps and lakes. The first birds appear about this time, evolving from several dinosaur species
- 165 M	J	No rocks of this age are exposed in this area	Possible meteorite impact at Upheaval Dome, Utah, could have caused severe local earthquakes and impact effects to Pagosa. Dome may be a salt diapir, however, with no local effects. Debate continues
- 160 M	J	No rocks of this age are exposed in this area	The area is a quiet and stable environment. The first grass and flowering plants appear
- 150 M	J	Entrada Sandstone: Piedra River canyon, Archuleta Mesa	Pagosa dries out and becomes an arid area of desert, salt flats, and alkali lakes
- 145 M	J	Morrison Formation, Wanakah Formation: Piedra River canyon, Archuleta Mesa	Mountains rise to the east; the area gradually sinks and floods, forming a semi-arid to temperate climate of lakes, rivers, and shoreline dunes; forests of palm trees, ferns, and deciduous trees dominate
- 145 M	J	Morrison Formation	Impact of large meteorite at Morokweng, South Africa creates 50-mile crater, with worldwide climate disruption
- 145 M	J	Burro Canyon Formation: Piedra River canyon, Archuleta Mesa	Pagosa is a region of rivers and floodplains. Dinosaur and sea life extintions at this time are probably the result of the Morokweng Impact event

YEARS AGO	GEOLOGIC TIME	ROCK FORMATIONS & LOCATIONS FOUND	MAJOR GEOLOGIC, ECOLOGIC & CLIMATIC EVENTS AFFECTING PAGOSA SPRINGS AREA
- 144 M	***Cretaceous Period Boundary***		
- 120 M	Symbol: K Mesozoic Era, Cretaceous Period	No rocks of this age are exposed in this area	The Cretaceous Western Interior Seaway opens from the northeast, slowly flooding the interior of Western North America. Pagosa is probably a low-lying plain near the western shoreline
- 105 M	K	Dakota Sandstone: Put Hill, Pagosa Lakes area	The Interior Seaway spreads, flooding the Pagosa area, a series of shallow sea floors, river deltas and tidal flats. The climate is temperate to subtropical
- 100 M	K	Mancos Shale: surface rock throughout the Pagosa Springs area	Pagosa is a sea floor, about 300 feet deep. Sea life abounds, including oysters, clams, fish, and ammonites. Fossils found today are sea shells, fish and shark teeth and scales, and acanthoceras ammonites
- 90 M	K	Mesa Verde Group: south and east of town, Mesa Verde National Park	Retreat of the sea exposes the area briefly, forming a series of islands, deltas, and beach dunes; Pagosa Springs has beachfront property for sale
- 80 M	K	Lewis Shale: Chimney Rock area	The sea advances, flooding the area again. Pagosa goes under. The sea is dominated by sharks, fish, and swimming reptiles. Fossils include a mosasaur found near Valle Seco.
-75 M	K	Pictured Cliffs Formation: Chimney Rock mesa and pinnacles; Cat Creek Gap	Final retreat of the sea as the Larimide Orogeny (mountain-building period) begins to raise the modern Rocky Mountains. Tidal flats and shoreline dunes fill in the old sea floor. Palm and conifer forests dominate; crustaceans burrow in the sandy shore. Fossils include petrified wood, leaf impressions, dinosaur bones, and ophiomorpha burrows
- 70 M	K	Fruitland Formation: South of Chimney Rock, Yellowjacket Pass	The old sea floor continues to rise. A long period of global cooling begins. Pagosa is a land of clam flats, peat swamps, and shallow lakes, with seasonal climate changes
- 69 M	K	Fruitland Formation	Short dramatic period of global warming coincides with onset of Deccan Traps (India) basaltic flood eruptions, through – 64 M years
- 68 M	K	Animas Formation: South of Chimney Rock, Yellowjacket Pass	Continued mountain-building dumps massive amounts of sediment into local river systems. Rivers become larger and more prone to seasonal flooding on a large scale
- 65 M	**Cenozoic Era Boundary/Tertiary Period/Paleocene Epoch Boundary**		
- 65 M	Symbol: K/T Cretaceous/ Tertiary Boundary Event	Animas Formation	Chixulub (K/T) Impact Event ends the Mesozoic Era and likely causes the Cretaceous Extinction Event. An asteroid impacts in eastern Yucatan, blowing out a 120-mile crater. Worldwide shock and thermal effects occur. Pagosa Springs is destroyed 4 minutes after impact; Canada is wiped out 10 minutes after impact. Planet-wide fire storms and tsunamis kill up to 70% of all life on Earth; oxygen levels drop drastically and are still recovering today. Virtually all large land animals die off, including all dinosaurs. Small land animals survive, including reptiles and mammals. Other suspected impacts and/or volcanic events 150,000 years earlier may have pushed some species to near extinction before the K/T impact event. The boundary layer in the Animas Formation has not been identified locally; it may have been removed by later erosion
- 65 M	Symbol: T Cenozoic Era, Tertiary Period, Paleocene Epoch	Animas Formation	Continued mountain-building occurs locally as world-wide ecosystems recover and change from the pre-impact ecology. Mammals and modern birds begin to occupy the old dinosaur econiches in a burst of rapid evolution; climate may still be cold and harsh
- 58 M	T	Animas Formation	Extreme global warming begins, perhaps triggered by destabilization of sea-floor methane hydrates; warming of world climate causes massive extinctions of deep-sea life forms and rapid species evolution of land mammals

YEARS AGO	GEOLOGIC TIME	ROCK FORMATIONS & LOCATIONS FOUND	MAJOR GEOLOGIC, ECOLOGIC & CLIMATIC EVENTS AFFECTING PAGOSA SPRINGS AREA
- 55 M	***Eocene Epoch Boundary***		
- 45 M	T	Blanco Basin Formation: Upper Blanco Basin	Intense mountain-building period begins as western North America moves west over a mantle hot spot, causing extreme erosion and sediment deposition. Pagosa is a landscape of alluvial fans and lakes, with a very humid climate, about 39"/year of rain, and frost-free winters
- 40 M	T	Blanco Basin Formation	Magma bodies penetrate the crust and begin a long period of volcanic activity in the southwest; ecozones change as volcanos build and alter local weather patterns. Pagosa becomes mountainous and subject to increasing volcanic devastation
- 36 M	T	Blanco Basin Formation, volcanic dikes and lava flows: Upper Blanco Basin, Wolf Creek Pass	Creation of the San Juan Volcanic Field, building of the local San Juan Mountains, caused by intrusion of several major magma bodies (batholiths) in the crust; volcanic eruptions increase in frequency and violence, in a cycle of destruction and recovery over millions of years; extreme ecological changes result locally over time
- 35.7 M	T		Two or more comets impact in Popigai, Siberia, and Italy, causing global cooling
- 35 M	T		Asteroid impact creates 65-mile-wide Chesapeake Bay crater, causing local cooling of climate
- 34 M	***Oligocene Epoch Boundary***		
- 28.8 M	T	Chiquito Peak Tuff: Wolf Creek Pass and San Juan Mountains north to Creede	Mega-eruption of La Garita Caldera Complex, largest volcanic explosion in known planetary history, creates a 70-mile crater and devastates the Four Corners; 1,200 cubic miles of debris are ejected in an eruption lasting about 3 days; layers of lava and ash over 1,000 feet thick are followed by smaller eruptions, mudflows, landslides, and floods; climate change results with average temperature dropping by 14 degrees
- 28 M	T	Creede, Platoro, Summitville	La Garita Caldera subsides and fills with numerous lakes, hot springs, and landslides, and smaller volcanic eruptions continue. Local climate is similar to today, with a mean annual temperature of about 40 degrees
- 27.5 M	T	Silverton area volcanic rocks Tuff of Crystal Lake: East Fork valley	Silverton Caldera erupts, dropping thick layers of tuff across the region; the Tuff of Crystal Lake is exposed in the East Fork valley at the 2008 landslide site
- 26.8 M	T	Creede Formation: Creede area	Hydrothermal activity emplaces rich precious metal deposits in volcanic calderas (Silverton, Creede, Summitville, many others) across the entire San Juan Volcanic Field
- 26 M	T	Intrusive igneous rocks, small dikes and stocks: throughout local area	Colorado Plateau rises, heated by mantle upwelling below the crust; the Rio Grande Rift opens, creating the San Luis Valley and Arkansas Valley; earthquakes and renewed volcanic activity disrupt the local ecology
- 25 M	T	Intrusive igneous rocks, hot spring deposits: throughout local area	Increased subsurface heating causes hydrothermal (hot ground water) systems to dissolve minerals from basement rock; numerous hot springs, geysers, and mud springs form. The Pagosa area is probably like the Yellowstone area is today, and the Pagosa Hot Springs appears, likely as a geyser

YEARS AGO	GEOLOGIC TIME	ROCK FORMATIONS & LOCATIONS FOUND	MAJOR GEOLOGIC, ECOLOGIC & CLIMATIC EVENTS AFFECTING PAGOSA SPRINGS AREA
- 24 M	***Miocene Epoch Boundary***		
- 22 M	T	Lake City	Lake City caldera eruption. The geothermal (hot water) system collapses as the heat dies away, and most of the local hot springs fail. The Great Pagosa continues to bubble
- 20 M	T	Intrusive dikes and sills: Wolf Creek Pass, Lower Blanco Basin	Gradual slowing of volcanic activity allows the local ecology to stabilize; intrusion of dikes and sills such as Jackson Mountain laccolith cause small eruptions; hot spring activity lessens; erosion begins to destroy inactive volcanic mountains, causing more floods
-10 M	T	Pagosa hot spring mineral deposits Intrusive dikes and sills: Jackson Mountain laccolith, lower Blanco Basin dikes, Trujillo-Pinon Hills Ranch dike swarm	Cooling of magma bodies causes faulting and settling of crust locally, reinvigorating some hot springs; locally, earthquakes increase in intensity and frequency; erosion destroys many old calderas and crater lakes. Minor volcanic eruption at Jackson Mountain cools magma laccolith beneath;probable fissure eruptions spread thin lava sheets across lower Blanco Basin and Trujillo areas; last significant eruption of volcanos locally marks the end of igneous activity in the Pagosa area. From now to the present, the major geological force affecting Pagosa is erosion from glaciers and floods
- 5 M	***Pliocene Epoch Boundary***		
-3.3 M	T		Asteroid impact in Argentina creates a 22-mile-wide crater; global cooling results, with extinction of 36 genera of mammals; 2 new genera appear
-3 M	T		Asteroid impact in the Southern ocean near Argentina generates mega-tsunamis which destroy the northern Antarctic and eastern South American coasts, followed by global cooling
- 2.6 M	T		A world-wide ice age begins; short advances and retreats of glaciers occur through the next 1 million years
-1.8 M	T		Period of global cooling and glaciation continues; San Juan Mountain volcanos are covered with snow year-round and glaciers fill valleys; cold, dry climate dominates the area. Glaciers advance and retreat in a cycle lasting to the present day
- 1.8 M	***Cenozoic Era/Quaternary Period/Pleistocene Epoch Boundary***		
- 1 M	Symbol: Q Cenozoic Era, Quaternary Period, Pleistocene Epoch	River deposits (alluvium) and glacial debris (till): high mountain valleys and stream channels	Beginning of Kansan Ice Age; major global cooling intensifies; sea levels drop significantly as water is trapped in continental glaciers. Pagosa area suffers intensely cold climate and forests are buried under glacial ice
- 300,000	Q	Alluvium, glacial till: East Fork Valley, Weminuche Wilderness	The Wisconsin Ice Age begins, and glaciers advance once again, burying forests and filling valleys with ice; erosion of Dakota Sandstone caprock may have begun around this time along Ice Cave Ridge during meltwater floods; retreating ice allows gravity to fracture caprock, opening long deep “ice cave” fissures
- 70,000	Q	Travertine: Pagosa Hot Springs area	Wisconsin glaciers retreat; the Pagosa Hot Springs geyser (?) activity builds a broad, thick platform surrounding the pools. Eruption of Toba Volcano in Asia may have killed 99% of human populations worldwide through intense climatic disruption; estimated 60,000 humans survive
- 50,000	Q	Alluvium, glacial till: San Juan River valleys; Put Hill crest; Chimney Rock area	Continued faulting at Put Hill raises eastern (Pagosa Springs) side and drops western (Pagosa Lakes) side, creating today’s local land surface. Floods from major retreat and melting of glaciers cause tremendous erosion, shaping modern landfroms such as Chimney Rock pinnacles; high mountain valleys begin to open up in summer and forests recover from intense glaciation; human populations recover worldwide and spread rapidly

YEARS AGO	GEOLOGIC TIME	ROCK FORMATIONS & LOCATIONS FOUND	MAJOR GEOLOGIC, ECOLOGIC & CLIMATIC EVENTS AFFECTING PAGOSA SPRINGS AREA
- 30,000	Q	Alluvium: local valley and stream channels	The first humans appear in North and South America, during several periods of low sea level and migrations from Asia; the Pagosa Hot Springs is cooling, and geyser activity may have been replaced by boiling pools around this time
- 20,000	Q	Alluvium	Another period of major glacial advance ends, with flooding from meltwater; global warming is underway and human populations are spreading rapidly across the Western Hemisphere
- 11,000	Q	Glacial till: high mountain valleys	Younger Dryas Glacial Period- a short but extremely intense period of glacial activity begins worldwide; elevations above 8,000 feet are icebound year-round; forests are destroyed by the advancing ice; as glaciers retreat, first Pagosans begin to use high mountain passes for summer camps and hunting sites
- 10,000	***/Holocene Epoch Boundary***		
- 10,000	Q	Worked stone artifacts; landslide deposits: mountain valleys and stream bottoms; Cintinental Divide passes	End of the Dryas Glaciation-major extinction of Ice Age mammal species across North America, including native horses, camels, lions, sabre-tooth tigers, cave bears, giant sloths, dire wolves, giant beavers, and many others. Floods and landslides dominate the local environment, from melting glaciers; humans begin seasonal occupation of the local river valleys, crossing mountain passes in summer; probable beginning of regular human use of the Pagosa Hot Springs and other local hot springs (Rainbow, Piedra, and others now extinct); Chimney Rock spires achieve their current form and are probably a local travel landmark to migrating tribes; Ice Caves fissures stretch across Dakota caprock above Williams, Weminuche canyons, preserving ice yearround
- 8,200	Q	Modern river sediments throughout area	A short, intense period of global cooling begins. High mountain passes are probably ice-bound and impassable for decades, disrupting human and animal migrations
- 8,000	Q	Modern river sediments and landslides throughout area; East Fork Valley, high mountain passes in the Weminuche Wilderness	Onset of present-day warmer period between glacial advances; the climate begins to warm, and the last retreat of the high mountain glaciers is complete. Massive flooding and landslides occur as meltwater and removal of ice weaken steep slopes carved by the glaciers; mountains and cliffs take their familiar forms, creating the Pagosa vistas of cliffs and peaks; conifer forests and modern mammal species dominate the local ecology
- 2,000	Q	Modern land surface	Local climate stabilizes, slightly cooler and wetter than today. Local hunter-gatherer cultures are replaced slowly by agricultural peoples from the south, settling in small farming villages and hunting local deer and elk herds
- 1,000	Q	Modern land surface	Little Ice Age in Europe begins; the local climate cools and becomes dryer. Indians occupy the area as year-round farming societies; great pre-Columbian cultures are flourishing (late Maya, ancestral Puebloan/Anasazi, and Cahokia) in western and central North America
Today	Q Cenozoic Era, Quaternary Period, Holocene Epoch	Today's mud, everywhere	Gradual warming of the global climate is underway, with an uncertain added influence from human activity. Local and world ecologies are affected by clearing and use of land by growing human population. Minor earthquakes and gradual cooling of local hot springs modify the area's geology slightly; landslides and stream-bed floods and deposition are the dominant geologic forces affecting Pagosa Country today

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The Geologic Story of Chimney Rock

Long before humans found the mesas and spires of Chimney Rock, this impressive landmark was created by the forces of nature: millions of years of slow settling of mud in a shallow sea; gradual drying of the sea and migration of beaches and rivers across the ancient basin; thick, humid swamps dominated by dinosaurs and giant insects; the catastrophic birth of mighty volcanoes and their scouring, deadly eruptions; slow but constant uplift and tilting of the land; millennia of glaciers and vast floods as they melted away; erosion of the exposed beach sands and ocean-bottom muds (now solidly cemented into rock); and - finally - the arrival of the first Americans to marvel at this incredible work of the Earth.

This quick overview of the long history of Chimney Rock is known from study of the rocks and from understanding of the processes that shape our planet - the science of ***geology***. Scientists today estimate that the Earth formed some 4.6 billion years ago, based on the age of rocks on Earth, the Moon, Mars, meteorites and the asteroids of the Solar System. Chimney Rock is far younger than that, however. The oldest rocks exposed here - the thinly bedded gray shales at the base of the mesa along Stollsteimer Creek - are thought to be about 90 million years old. This is only 1/5 of 1 percent of the Earth's age (in human terms, the same as the final 2 months of a life span of 80 years).

Chimney Rock's twin spires are entirely natural in origin, not the work of Man. They are an erosional remnant of a thick sequence of sedimentary rock laid down in the late Cretaceous Period, from about 100 to 70 million years ago. The oldest rocks exposed in the area (to the north of Chimney Rock) are the terrestrial and marine-shoreline sandstones and siltstones of the Mesa Verde Group; above these beds lies the shallow sea-bottom Lewis Shale, which forms the slopes and canyons of the Chimney Rock area. The shales are capped by the tidal, beachfront, and river sand layers of the Pictured Cliffs Sandstone. It is this unit that forms the mesa tops and the dramatic stone pillars of the Chimney Rock formation. Erosion has removed the rock units which once lay above the Pictured Cliffs Sandstone, but these rock layers are exposed to the south of Highway 151 and into northern New Mexico. From bottom to top (older to younger in age), they are the Fruitland Formation, a late Cretaceous sequence of swamp, floodplain, and shallow lake sediments; the Kirtland Shale (included in the Fruitland here), a late Cretaceous deposit of shallow marine mud flats; the Animas Formation, a thick series of terrestrial deposits eroded from the rising mountains to the north, spanning the latest Cretaceous and earliest Tertiary Periods and therefore witness to the extinction of the dinosaurs and early rise of the mammals; and the Blanco Formation, more terrestrial debris interspersed with layers of volcanic ash from the violent eruptions that shattered the land starting about 30 million years ago.

Evidence from fossils, sediment types and structures shows that the climate was temperate to subtropical, warmer and wetter than today. This area was probably located much nearer the equator (perhaps near 15 degrees north latitude; today it lies at 37 degrees north). Geochemical evidence supports the presence of a higher oxygen content in the atmosphere, perhaps 15 to 20 per cent more than today. Forests of palm trees, hardwoods and conifers covered the shorelines. Shallow lakes and wide floodplains bordered the sea, and the shoreline gradually migrated across the area. Shoals of clams and oysters lay exposed during low tides, and ripples show the ebb and flow of the sea water across the sand flats. Small creatures called ophiomorpha left their knobby, branching burrows in the beach sand. Dinosaurs such as the hadrosaur, a herd-living herbivore, and the sea-dwelling giant lizard called the mosasaur, were among the larger animals here. Crocodiles, turtles, sharks, rays, and numerous other creatures shared the land and sea. Floods occasionally swept across the land, but generally, life was thriving. This period saw the takeover of the skies by the first birds, the rise of flowering plants, and the first spread of grasses across the world.

Chimney Rock's beaches and floodplains were already millions of years in the past when the dinosaurs were extinguished, 65 million years ago, but the rock layer that records that disaster lies not more than a few hundred feet above Chimney Rock's highest point, at least stratigraphically (as the rock layers originally were deposited). In general, sedimentary rocks are deposited in relatively horizontal layers, so the numerous rock beds that make up the Chimney Rock country were originally flat. But deposition is not the only force in geology that shapes the land. As the North American continent broke apart from the supercontinent of Gondwanaland and drifted west on its tectonic plate, it began to stretch and buckle. Locally, the great depression called the San Juan Basin formed in northern New Mexico and today's Rocky Mountains began to rise, a time known as the ***Larimide Orogeny***. The land between these two geologic provinces lifted and tilted to the south. Its northern edge fractured, folded, and crumpled, cut by faulting and breached by erosion. These rock layers are exposed as 45-degree tilted beds along the north side of US Highway 160, west of the Piedra River. Further south, though, the rocks lay in a smooth slope of about 7 degrees, dipping into the northern edge of the San Juan Basin.

Erosion proceeded to remove the rock layers as they were uplifted. The rising mountains to the north and other worldwide climate factors altered weather patterns. From the early ***Pleistocene Epoch*** (about 2 million years ago), glacial periods also affected the climate. It is likely that the Pictured Cliffs Sandstone was exposed as a narrow ridge during the latest Pleistocene or earliest Holocene, about 100,000 years ago, probably as a series of spires and walls and possibly arches. After the most recent retreat of the Wisconsin Glaciation (about 15,000 years ago), the most active erosion ended, leaving the twin formation we call Chimney Rock, standing free of the softer shales and weaker sandstones that once surrounded and covered it.

Such is the technical description of the geology of this amazing area. However, geology can also be seen as a story; what follows is an attempt to capture the feeling of that long sweep of history. About 100 million years ago, the North American continent was divided by a shallow ocean, known to geologists as the ***Cretaceous Western Interior Seaway***. This sea stretched from Mexico to Canada, its western shoreline passing close to the present-day site of Chimney Rock. Most of southwestern Colorado was under water, and a blanket of fine mud and clay constantly settled to the bottom of the sea. This thin, even layering of gray sediment accumulated at the rate of an inch every thousand years. For twenty million years this went on, building up almost 2,000 feet of mud. Sometimes a storm or flood would dump a layer of silt or sand far out into the sea, but these sediments were buried in the mud once quiet times returned. Microscopic animals and plants, and their larger swimming or floating cousins, died and were entombed in the soft ooze, leaving evidence of their forms and the environment in which they lived.

Change is constant in nature, and even oceans vanish. Gradually, the North American continent moved west, riding currents generated in the depths of the planet's semi-molten mantle, and was carried over a "hot spot". This immense upwelling of superheated magma stretched and raised the crust, building the Rocky Mountains north of Chimney Rock's future site. As the land was lifted, the ocean began to drain away to the south. This took many thousands of years, and the shoreline, with its beaches, tidal flats, and river deltas, followed the ocean's retreat. A thick layer of sand and silt buried the ancient ocean-bottom muds below. Forests and swamps followed in turn, sliced by wandering rivers and their floodplains and backwaters. The Age of Dinosaurs was in its final flower, and shoals of clams and oysters added their shells to the sediment alongside the bones of the great beasts. Trees fell, swamps flooded and drained, and a vast layer of fossil-bearing sediments and coal seams formed above the sandy beaches of the buried shoreline. Palms and conifers and hardwood trees dominated the forests, and the world's first flowers and grasses spread across the land. By 70 million years ago, though, there is absolutely no sign of Chimney Rock - it is still part of a distant future contained in those buried beach sands.

The land continued to rise. Forced up from below, eaten away by the molten magma beneath the crust, the rocks weakened. About 65 million years ago the dinosaur age ended, perhaps the victim of continental breakup, changes in environmental conditions, worldwide epidemics of new diseases, or, most dramatically, a massive asteroid impact in Yucatan. The crisis, whatever caused it, ended a reign of 200 million years for these amazing beasts; mammals inherited the Earth and birds took the skies for their own. Volcanoes penetrated the weakened crust, piling up mountains that surpassed the famous Fourteeners of today's Rockies. Sheets of lava, rains of pumice, and scalding clouds of ash swept down on the forests and swamps, burying them and their ecologies, only to surrender to the tenacity of life once the eruptions ended. Over and over this cycle played itself out, laying down thousands of feet of debris over tens of millions of years. And still the future Chimney Rock slept in the fossilized sands of that ancient shoreline.

Then, some 28 million years ago, the volcanic activity peaked in a final cataclysm. A series of eruptions culminated in a blast some 10,000 times the force of Mount Saint Helens' eruption of 1980, pulverizing and lifting an estimated 1,500 cubic ***miles*** of rock into the skies over the Four Corners. There is no way for us to even imagine the devastation it must have caused, but certainly life was devastated for hundreds of miles in every direction. The crater complex (known today as the ***La Garita Caldera***) extends from Wolf Creek Pass north to Alamosa, nearly seventy miles across. To the south, the continent itself began to split apart, opening into a long, narrow rift from southern New Mexico to southern Colorado - today we call it the Rio Grande Valley. If the opening had continued, there would be a sizable ocean there today, and Pagosa Springs, Santa Fe, and Albuquerque would be seaports.

But the volcanoes began to die, robbed of their heat energy as the continent moved past the hot spot. The rifting stalled, the eruptions slowed, and the land began to recover. The slowly cooling chambers of magma would take millions of years to crystallize, a process that is still not complete to this day, and they still send up small spurts of lava and boiling water across the southwest.

Arizona and New Mexico have seen the force of volcanic eruptions as recently as a thousand years ago, and may yet experience those convulsions of rock and lava. The Great Pagosa Hot Springs and innumerable other hot and warm springs across the region attest to the heat still trapped below. The Four Corners still occasionally trembles from earthquakes, as the land settles. But the rifting and the growth of the San Juan Mountains was over. Erosion now took the reins as the driving force shaping the land. The dead volcanoes weathered, shedding huge blankets of rock and soil into the rivers. Rolling hills and wide river valleys sloped and drained into the San Juan Basin to the south, in modern New Mexico. The earth spiraled into a glacial age. Cool, wet summers and icy winters ruled this part of Colorado. Glaciers sculpted the land, scouring the sides of mountains and valleys, pouring broken rock and sand and clay into raging rivers of melt water. The tilted layers of ancient sea bed, shoreline beaches, swamps and river deposits, long buried by the overburden of volcanic debris, began to feel the nearness of light and air as the rivers tore away at the rock above them.

Finally, about a hundred thousand years ago, erosion exposed a thick sand layer, the beach and dune field of the lost Interior Sea's ancient shoreline. This sand layer was hard and resisted the erosion of the nearby river. The waters found the surrounding shales of the sea bottom a much easier victim, and they scoured away the fossilized mud, leaving a long, meandering wall of sandstone standing high over the valley floor. It would have fallen to the persistent river eventually, but the glaciers that fed the river melted away as the climate warmed into today's interglacial period. Deprived of their power, the rivers retreated and shrank, and the ancient sand bed remained high and proud.

Catastrophes continued. About 50,000 years ago, just a few hundred miles to the west near the future site of Winslow, Arizona, a chunk of stone the size of a football field slammed into the Earth, blasting out today's Barringer Meteor Crater. Were people here yet, to witness, and perhaps perish from this violent explosion? No one is sure, but by about 30,000 years ago, human beings were colonizing the New World, migrating in waves from Asia, exploring every part of this new land. Mammoths and mastodons, the great cave bears and saber-toothed tigers and dire wolves, the giant sloths and the American lion, horse, and camel - all the beasts of the glacial age - were disappearing. Climate changes were the likely primary cause, but the new, deadly predator called Man may have helped.

The spine of sandstone was safe from the erosive power of the shrunken Piedra River. But Nature constantly strives to wear down the Earth, and if a river isn't available, the shattering effects of heat and ice, and the blasting of wind will do the trick. Earthquakes also did their part, and pieces of the stone wall cracked, crumbled, and fell away. Perhaps it started as a solid rampart, pierced finally by windows and arches, or soaring bridges - but eventually, there stood two massive pillars, twin towers of stone, guarding the pass from the deserts of the south into the mountains of the Continental Divide.

And so, about 1,000 years ago the ancestors of today's Pueblo People found this place, and made it home for a time. Perhaps they wondered at the fossil dinosaur bones, the petrified palm trees and conifer wood, the layers of clams shells turned to stone. Maybe they recognized the ripples frozen in stone as strange cousins to the ripples of sandy stream bottoms. Did they realize that the black impressions in the stone were actually the leaves of trees and ferns that once grew along the shore of an ocean? We will never know, for they did not record their thoughts and beliefs for us to read.

We do know that they used the rocks, for tools, shelter, weapons, and adornment: agate and chalcedony and chert and petrified palm wood to make arrowheads, basalt and granite for axe heads, sandstone for corn grinders and pueblo walls, clay to form pots and mortar and plaster, volcanic glass for knives and spearpoints, powdered limonite and ochre and malachite and caliche for the vibrant yellows and reds and greens and whites of their paints, turquoise to cut into beads and pendants and tooth inlays... the geologic bounty of the Earth has shaped human hands and minds over our entire history. The shape of the rocks themselves may also have drawn the people here, to celebrate the twin pillars of stone on their high mesa.

They were not here long, as human history goes- they first settled at Chimney Rock around 900 AD and they were gone by about 1125 AD. Perhaps the eruption of Sunset Crater in central Arizona affected the climate in the area, but cultural patterns across the Southwest were changing anyway. For whatever reasons, they left their homes at Chimney Rock and settled in today's Pueblos along the Rio Grande and in other parts of Arizona and New Mexico. They left us no written records to ponder. The rocks still tower over their city, high above the river named in 1775 by Dominguez and Escalante as ***El Rio de la Piedra Parada*** - the River of the Standing Rock. The twin pillars' appearance has changed little from that time. After all, in the history of the Earth, a single millennium is nothing.

Interestingly, two of modern man's most coveted prizes from the Earth - gold and coal - were ignored by the people of Chimney Rock. Only in the last two hundred years have miners dug and sifted and scoured the land for "the tears of the Sun" and "the rock that burns". Maybe the ancestral Pueblo people wondered at the soft, heavy metal when they found it in the sand of the stream bottoms; did it really drop from the Sun, as their Mexican cousins thought? As for coal, they may have known that it would burn. Forest fires regularly set coal seams on fire, and the blazes can burn for years or decades or centuries. But coal fires smell bad, and the people probably had no need for the intense heat of a coal oven. Ground coal makes a good black paint - did they use it for ceremonies? Almost certainly, they could not have guessed that the thin, crumbly black rocks under their feet formed in hot, humid swamps roamed by dinosaurs and small ratlike mammals.

And what about the future? Barring an earthquake, the Chimney Rock pinnacles should easily endure another fifty or hundred thousand years. Nature will eventually triumph, however, and sweep them away, grain by grain, to the ocean floor - the ultimate doom of all rock. Someday the minerals of which the rocks were once made will reappear, thrust up into new mountains or volcanoes, in a new form, and the cycle will start again. For now, we enjoy their majesty and marvel at their history, short as it is in geological terms. For the ancestors of the Pueblo Indians, though, the Rocks were eternal.

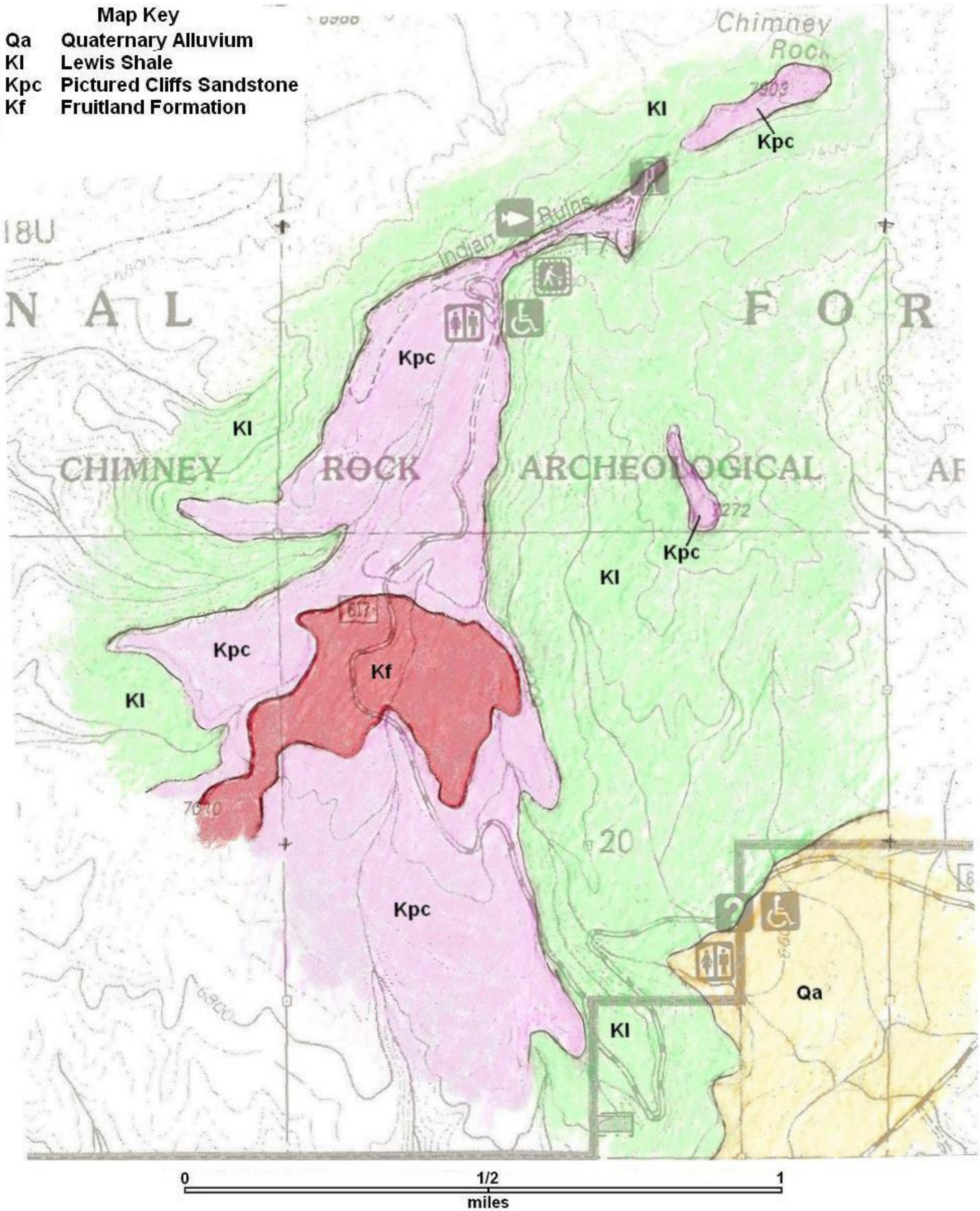
Photo copyright Mark Roper

This photograph was taken from Highway 160, just off of the northwest (upper left) corner of the geologic sketch map below, looking southeast (toward the lower right) at the ridge line. The thick, fractured layer of white stone forming the twin rock spires of Chimney Rock (left) and Companion Rock (center) are made up of the Pictured Cliffs Sandstone (Kpc on the geologic sketch map), a layer about 300 feet thick. The Forest Service fire lookout tower (right) sits on the same rock layer, near the bottom edge of the layer- erosion has removed most of the rock layer, leaving only the lowermost 20-40 feet.

Below the Pictured Cliffs Sandstone is the thinly layered Lewis Shale, made up of compressed clay and mud of the shallow Cretaceous Inland Sea floor. As the ancient sea gradually filled, the sands of the shoreline beaches, dunes, tidal flats and river sediments built up the Pictured Cliffs Sandstone above it. The Lewis Shale is about 2,000 feet thick in this area. Here, only the uppermost 900 feet or so are exposed. The shale just below the Pictured Cliffs Sandstone has an age of about 72 million years. This age is from a known world-wide magnetic-field reversal date, determined by a study done in the late 1980's.

The Ancestral Puebloan Great House, built 1,000 years ago by peoples of the Chaco Culture, sits just to the right of the lookout tower, constructed of fragments of Pictured Cliffs sandstone, cemented together with mud made from the clay of the Lewis Shale.

GEOLOGIC SKETCH MAP OF CHIMNEY ROCK



Top of map is North.

Refer to the Pagosa Country Geologic History Table for information on the geologic formations.

Treasure Mountain Geology and Lore

Treasure Mountain stands at 11,908 feet. It is a dominant peak within the South San Juan Mountains, close to and west of the Continental Divide within the Pagosa Ranger District of the San Juan-Rio Grande National Forests, in Mineral County, Colorado. The South San Juan Mountains were formed by and are the erosional remains of the San Juan Volcanic Field (Steven and others, 1974), a complex of overlapping volcanoes, eruptive and intrusive rocks, and calderas which generated some of the largest and most violent volcanic eruptions on Earth (Lipman and others, 1996). Treasure Mountain and its adjacent landforms are also the site of the spectacular Treasure Falls, beautiful hiking trails, and unsurpassed high-country scenery and vistas. The mountain's geologic roots have, in addition to its natural beauty, inspired other desires; a persistent and colorful legend of a lost and found and lost again golden treasure has given the mountain its present name (Adams, 1993; 1996).

Treasure Mountain is founded in volcanic violence. It is made of layers of tuff, a rock composed of pyroclastic material. Pyroclasts are particles of rock ejected into the air by volcanic eruption; they can be of any composition, from felsic (high in silica content, low in iron and magnesium) to basic (low silica, high iron-magnesium). Typically, pyroclasts cool quickly and have little or no crystal component, being instead frothy or vesicular (as in pumice or scoria), or vitreous (as in obsidian, volcanic glass). Tuffs can be loose and poorly consolidated, easily weathered and eroded, or strongly bonded by the heat of their volcanic origin ("welded") to form resistant layers of rock. Treasure Mountain's environment has both types of rock.

The mountain itself is composed of the Treasure Mountain Tuff (Steven and others, 1974; Brock and Gaskill, 1985; Lipman and others, 1996). The upper 1000 feet of the mountain is made up of the Upper Member, Ra Jadero Member, Ojito Creek Member, and Middle Member - layers of tuff deposited by air-fall and ash flows. The source of the tuff was the Summitville caldera to the east. Below this series of tuff layers is the La Jara Canyon Member, about 600 feet thick, a biotite-pyroxene-plagioclase-quartz latite ash flow. This layer erupted from the Platoro caldera to the southeast. Forming the slopes and local terrain around the mountain's base is the Lower Member, more air-fall and ash flow tuff.

The wider landscape around and below the mountain is composed of rock called volcaniclastic, which is a sedimentary rock made up of volcanic material moved and redeposited by streams and rivers, before it has been compacted into rock. This process usually occurs soon after the eruption has deposited its debris across the landscape, when rain and snowmelt attack the fresh, loose volcanic debris. Thick layers of this volcaniclastic rock extend many miles south and west from Treasure Mountain, and form the ledges and cliffs over which tumble the waters of Treasure Falls, about 3 miles west of the mountain's peak.

To the northeast lies Treasure Pass on the Continental Divide, made up of layers of the Masonic Park Tuff, a biotite-pyroxene-plagioclase-quartz latite ash flow which originated from the Mount Hope caldera.

All of these volcanic and volcaniclastic rocks are dated to about 28-30 million years in age, the Oligocene Epoch of the Cenozoic Era of geologic time. Numerous volcanic centers were in constant eruption throughout this period; southwest Colorado lay at the northern end of a massive crack or rift in the Earth's crust, today's Rio Grande valley. Recent studies (Lipman and others, 1996) show that this rift, this break in the crust, generated the most massive volcanic explosion known to man - the La Garita-Platoro caldera - which released 10,000 times the raw energy of Mount St. Helens' 1980 eruption, and pushed an inconceivable 1,000 cubic miles of pulverized rock into the air. Everything in the Four Corners must have been laid waste. No other volcano in known geologic history has been as violent.
Minor volcanic activity continued, but the major eruptions ceased about 15 million years ago. Small bodies of molten rock worked up through faults, forming dikes and sills, and small shallow pools

between older rock layers called laccoliths (lake-shaped). These small formations make up some of the local peaks such as Jackson Mountain. Erosion constantly ate away the mountains built by the volcanoes, wearing down their peaks which may have topped 18,000 feet in their prime. Most of the mountains of today are the slopes and outlying skirts of the older volcanoes - their towering hearts were blown out of existence during those titanic eruptions. Within the last several million year, glaciers buried the slopes and lower peaks in ice and gouged out valleys below. Today's landscape is largely the result of those rivers of ice. Thick blankets of eroded material, glacial drift, alluvium, landslide debris, are the product of these years of glaciation and the flooding as the glaciers finally melted away.

Although this monumental volcanic field seems today to be quiet, it has left a legacy of volcanoes, hot springs, and lava flows which continue to be active to the present day. Volcanoes have erupted in New Mexico and Arizona only a few thousand years ago (an instant in geologic time), and hot springs continue to pour out the heat of molten rock just beneath our feet. Earthquakes shake the mountains and valleys around us, as the rocks below cool and settle.

Another legacy - as important to humans as scenery and mountain streams - is the gleam of gold. Deposits of gold and silver were created as the volcanoes cooled and their magmas crystallized. In place in the hard rock, or weathered out and tumbled into the sands of thousands of stream beds, the precious metals drew explorers and settlers to this area. According to legend (Adams, 1993;1996), a group of French miners found rich gold deposits in and around Treasure Mountain and the East Fork Valley, and set to mining them. But this was the late 1700's and this land belonged to Spain and the Indians. The trespassers were slaughtered by the Indians in Spain's employ, leaving the hidden caches of gold bars and nuggets lost to history. Except - there was one survivor, and he had a map. Years later, when the United States became the owner of the mountain, he returned. Did he find the gold? Stories say yes. But to this day, people explore the mountain - Treasure Mountain - in the hopes that some of that lost treasure is still out there.

Small gold flakes and even a few nuggets can be panned from the local rivers. Several small mines exist today, wrenching a little precious metal from the rocks. Summitville, Creede, Bonanza, and other famous rich strikes are history, but gold does remain in the mountains - ironically, now too costly to mine; society puts a higher worth on this land and its living things. As for the future, it is unlikely that the volcanoes will awaken in human lifetimes. But the Earth has many millions of years ahead of it, and the Rio Grande Rift may once again open.

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A Relic of Chixulub? *A Geological Whodunit*

The southwestern part of the Pagosa Ranger District, San Juan National Forest, lies along the northeastern edge of the San Juan Basin, a Late Cretaceous to Early Tertiary age asymmetric structural depression 120 miles in diameter, formed during the Laramide Orogeny (Ayers Jr. and Kaiser, 1994). About 9 miles north of the town of Pagosa Springs, a road cut along US Highway 160 exposes an outcrop of the upper Cretaceous Pictured Cliffs Sandstone and the conformably overlying, locally undifferentiated Kirtland Shale-Fruitland Formation. These units represent the last regression of the Cretaceous Inland Sea in southwestern Colorado. The Pictured Cliffs Sandstone is a 300-foot-thick unit of shallow marine, tidal-flat, beach and dune sands (Steven and others, 1974) with some fluvial-deltaic reworking, exhibiting cross- and laminar bedding, ripple marks, scour and point-bar sequences. It transitions and intertongues locally upward into the delta-floodplain-swamp complex of the 400-foot-thick Fruitland Formation (Steven and others, 1974), deposited during the change from beach-shoreline to onshore back-barrier floodplain-delta environment (Ayers Jr. and Kaiser, 1994). This unit exhibits interbedded shales, siltstones, coal seams, and in some locales, shoals of pyritized clams and oysters. The sequence in the Pagosa Springs area is generally undisturbed by the later tectonic and volcanic activity that created the San Juan Mountains (Ayers Jr. and Kaiser, 1994) and the San Juan Volcanic Field, site of the postulated world's largest caldera eruption (estimated eruptive volume of more than 1,200 cubic miles of ejected debris) about 28 million years ago (Lipman and others, 1996; Lipman, 1997). Regional dip is 4 - 7 degrees to the southwest toward the San Juan Basin.

The Highway 160 outcrop is a fascinating exposure. It consists of a conical mound protruding from the west bank of the San Juan River channel about 30 feet high and about 100 feet wide at the base, sliced almost in half by the highway. The lower ¾ of the exposure is Pictured Cliffs Sandstone, covered with a thin veneer of the lowermost Fruitland Formation; the upper Fruitland and Kirtland Shale have been truncated by an erosional surface, covered by about 1-2 feet of soil. The Pictured Cliffs Sandstone in the outcrop exhibits intense deformation: disruption of bedding, apparent liquefaction trails and channels, transportation and rotation of large blocks of consolidated and lithified sandstone, and central upheaval, penetration, and edge-collapse of strata. The Fruitland layer is more cohesive, wrapping over the mounded and deformed Pictured Cliffs like a blanket, but it is deformed as well: small-scale movement along faults, collapse into underlying Pictured Cliffs, and well-developed overturning and vortex-spiral features mark the edges of the mound. The impression is of a large "sand volcano"; large-scale soft-sediment deformation originating in the Pictured Cliffs and puncturing the overlying swamp deposits, apparently the result of a violent dewatering of the Pictured Cliffs semi-lithified sand/sandstone layer.

Such features are not uncommon when gravity loading and sudden shock disturb a water-matrix-supported buried sand layer. Small-scale soft-sediment deformation is a normal effect of burial and dewatering of saturated sediment, at bedding-plane scales (a few inches to several feet). Differential compaction occurs normally as well, as sands, clays, and peat compress at different rates; this typically affects formations across scales of hundreds of feet to miles. Earthquake-generated seismic liquefaction is a well-known example of such events on a similar to much larger scale. Small examples of soft-sediment deformation in the Pictured Cliffs and large examples of differential compaction in the Fruitland are known (Ayers Jr. and Kaiser, 1994). Fossil preservation of "sand volcanoes" is not reported from the Pictured Cliffs Sandstone, but since such structures tend to be on the scale of less than 50 feet, the chance of one being fortuitously exposed for study is understandably low. The generator of the event exposed by the Highway 160 road cut is unlikely ever to be positively identified, but circumstantial evidence can be considered.

When did the deformation occur in the depositional history of these formations? The Pictured Cliffs Sandstone and overlying Fruitland Formation contain fossils dates of Campanian to Maestrichtian (within a range of 83 to 65 million years) in age; fossil evidence also indicates that the northeastern

Pictured Cliffs-Fruitland sequence is about 3 million years younger than the southwestern part of the sequence (Fassett and Hinds, 1971). The Kirtland Shale, conformably overlying the Fruitland (absent in the outcrop area due to erosion) is fossil-dated as very latest Cretaceous and earliest Paleocene (Fassett and Hinds, 1971), placing an upper limit on the underlying strata's age. The Animas Formation which conformably overlies the Kirtland Shale is dated as containing the K-T boundary (65 million years). Allowing a reasonable estimate of time for these overlying formations to be deposited, the Pictured Cliffs-Fruitland Formation sequence can therefore be approximated at between about 78-70 million years in age.

The outcrop contains consolidated, cemented blocks preserving original bedding structure, bounded by rounded, disaggregated edges, inconsistent with typical fracturing of solid rock. These blocks have been rotated and moved out of position, and are surrounded by unconsolidated, structureless channels and pockets of disaggregated sand grains; there is no evidence that these deposits are the result of mechanical or chemical disintegration of well-lithified rock.

Sandstone diagenesis is controlled by numerous factors, but depth of burial and time since deposition are among the most important. Deeper burial and longer elapsed time generally result in a higher degree of compaction and cementation, especially for carbonate cement such as that of the Pictured Cliffs Sandstone. Time scales of several million years since deposition and burial depths of less than a few thousand feet are not typically sufficient for full lithification of relatively clean sands. The evidence of partial or limited cementation in the outcrop supports the timing of the disturbance as during early stages of diagenesis: shallow burial and shortly after deposition. Coal diagenesis occurs more swiftly, depending more on temperature of burial than time after deposition. Higher geothermal gradient promotes faster coalification. The Fruitland coals are bituminous in rank, indicating shallow/low temperature burial.

The conformably underlying Lewis Shale, a shallow-marine basin deposit, is unlikely to have contained concentrations of water or gas sufficiently localized or pressured to disrupt the overlying sedimentary layers. Conversion of the overlying Fruitland peat deposits to coal occurred between deposition across the abandoned shoreline deposits of the Pictured Cliffs and differential compaction in the Fruitland (Ayers Jr. and Kaiser, 1994); the coals were brittle when the outcrop deformation occurred. Differential compaction is a normal process of sand to sandstone diagenesis, but does not seem adequate to create the local and highly contorted nature of the Highway 160 outcrop. All of the above-noted factors indicate that a gross estimated time window for the event would be between 73 and 65 million years ago. It cannot have occurred after the Pictured Cliffs Sandstone was well lithified, which limits the time window to perhaps 5 million years after lithification of the precursor sands began. The largest unknown of course is the exact depositional time for the Pictured Cliffs Sandstone in the outcrop area. This seems the most critical limit for this proposed origin theory; if the Pictured Cliffs sands began lithifying before about 73 million years ago, they may have been too well lithified to undergo catastrophic local dewatering during the K-T boundary impact event.

Figure 1: Southern section of sand volcano - *note detached segments of Fruitland coal seam drawn down into probable water escape channels (left center and upper right) and rotated blocks of lithified Pictured Cliffs sandstone surrounded by chaotic structureless sand. The lithified blocks retain original sedimentary structure (cross-bedding, graded bedding, fossil burrow filling); most block edges are rounded and show signs of abrasion, probably due to violent rotation and tumbling during initial dewatering disruption and final collapse of sand volcano water escape channels.*

***Figure 2: Northern section of sand volcano** - note conformable layer of Fruitland coal seam along upper right surface of exposed sand volcano mound, and detached segment of Fruitland coal seam drawn down into probable water escape channel (upper left). Rotated blocks of lithified Pictured Cliffs sandstone are surrounded by chaotic structureless sand. The lithified blocks retain original sedimentary structure (cross-bedding, particle size gradation, fossil burrow filling); most block edges are rounded and show signs of abrasion, probably due to violent rotation and tumbling during initial dewatering disruption and final collapse of sand volcano water escape channels.*

Did local volcanic events or the intrusion of volcanic or geothermal fluid or gas cause the deformation? The San Juan Mountains are volcanic in origin, and of unsurpassed violence in nature. The onset of volcanism in the outcrop area was around 35 million years ago (Lipman and others, 1996; Steven and others, 1974), culminating in the postulated La Garita caldera eruption, the largest known volcanic explosion in Earth's history (Lipman, 1997; Lipman and others, 1996). Minor volcanism continued until about 4 million years ago. The Pictured Cliffs Sandstone was therefore well lithified before any local volcanic activity started. Thin layers of volcanic ash are found throughout the Pictured Cliffs and Fruitland beds (Ayers Jr. and Kaiser, 1994), but these are evidence of distant eruptions, not local ground-shaking events. As noted above, the Pictured Cliffs outcrop does not exhibit post-lithification mechanical or fracture characteristics, which would be expected of a volcanic breccia pipe. There is no evidence of thermal effects on the surrounding or overlying sediment, as would be expected from operation of a geothermal spring, hydrothermal conduit, or magmatic intrusion. No sinters, alteration products, or mineralization are present. Local magmatic intrusions (Blanco River dikes, Jackson Mountain Laccolith) and the well-studied Pagosa Hot Springs show the effects of such events and systems on the local formations; none of these effects are present at the outcrop. The known volcanic and geothermal events of the area apparently did not cause the observed deformation.

Did regional or local tectonic forces cause the deformation? The age of the sediment is critical in considering this question. Dewatering-related deformation is limited to the period closely following burial of the sediment, before consolidation and cementation fix the sand grains in place. The Pictured Cliffs and overlying Kirtland-Fruitland date to between 78 and 70 million years ago, and lithification could be expected to end the period of instability for these sediments by about 65 million years ago, as noted above. Well-developed north-south fracturing controls the local erosion and drainage patterns that originally exposed the outcrop, before highway construction enhanced it, but these patterns likely developed during the uplift of the Colorado Plateau (Ayers Jr. and Kaiser, 1994), after Pictured Cliffs lithification must have been well advanced. However, local structural folding bordering the San Juan Basin shows that the area was under stress prior to Larimide uplift (Ayers Jr. and Kaiser, 1994), so tectonic forces could have generated seismic events strong enough to activate the dewatering. A powerful local tectonic-generated seismic event cannot be ruled out as the cause of the deformation.

Could Chixulub be the culprit? The timing seems right. The Pictured Cliffs at 65 million years ago was possibly a water-saturated, perhaps water-supported sand layer, buried under hundreds of feet of heavy, water-saturated clays, brittle coals, and silts, with additional loading by the late Cretaceous deposits of the Kirtland Shale and lowermost Animas Formation (which spans the Cretaceous-Tertiary boundary in the area). Broad uplift of the Colorado Plateau may have induced local seismic events, but the local area was relatively stable. Lithification of the sands progressed slowly, cementing large segments of the Pictured Cliffs sediment from numerous nucleation zones. No significant volcanic or geothermal events occurred locally during these years. At about 65 million years ago, the Chixulub asteroid impact occurred along the future northeast coast of the Yucatan Peninsula, sending seismic shock waves across and through the planet. These shock waves would have encountered a sand layer that was at the cusp of balancing forces, and could have triggered a massive, instantaneous destabilization. Water and sand, still partly uncemented, liquefied and flowed upward under the pressure of gravitational collapse, disrupting the depositional structure of the uncemented sand and the overlying swamp deposits and brittle coal seams. The central flow zone rose, while the rims collapsed, sucking swirls of Fruitland coal and silt into the edges of the "volcano". A short-lived eruption of water and sand and entrained debris added to the chaos of the seismic and thermal devastation of the asteroid-impact shock waves at the surface, leaving the Pictured Cliffs sands below to settle into their new and more stable structure.

Something like this seems a good fit for the observed features of this outcrop. Whether Chixulub actually triggered the release of the formation's water, or it was caused by some other event, may not be knowable. But the possibility that in this small exposure we see a fossilized relic of that violent day, makes the speculation worthwhile.

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Mosasaur!

Picture a day in Pagosa Springs… the sun is shining, the west wind is brisk and warm. White foam blows from the wave crests. Along the distant shoreline, palm trees shimmer in glossy green.

Sounds strange? Palm trees, waves… in Pagosa Springs? Ah, but this summer day happened about 80 million years ago. The future Pagosa Springs lay on the muddy floor of a shallow inland sea, beneath 300 feet of salt water. Ammonites and fish and oysters and clams shared the sea. But the top of the food chain was the domain of the mosasaur.

Imagine a sea-going shape like a crocodile, 30 to 40 feet long, with flippers instead of feet. Imagine a three-foot-long set of jaws, armed with serrated steak-knife teeth. Imagine these jaws could flex on two different sets of joints, to expand and swallow big chunks of whatever came close. Imagine eyes, searching, always searching for something to eat. And add a powerful tail, pushing this sleek monster forward like a torpedo. This was a mosasaur.

Mosasaurs were not dinosaurs, although they shared the earth with them. They were reptiles, like today's lizards, snakes, crocodiles and alligators. Dinosaurs ruled the land, birds shared the air with the flying pterosaurs, but reptiles owned the seas. Mosasaurs, plesiosaurs, ichthyosaurs, these creatures formed the top layer of predators in the water. And, about 80 million years ago, one of them died.

We don't know how this monster died, whether of old age, sickness, or injury from another predator. But it was an adult when its life ended. The body may have been scavenged by other carnivores, but it was not torn apart and scattered – it seems to have settled to the soft, mud-layered ocean bottom in one piece. It is likely that the deeps of this sea were stagnant, lacking oxygen, and the mosasaur was slowly buried without further attack by living creatures. In time, the gently settling mud built up over it, entombing it and preserving it.

Time does not mourn the death of one mosasaur. The centuries, the millennia rolled on. The land moved west, riding its tectonic plate. The Colorado Plateau rose, forced upward by immense upwellings of molten rock beneath the earth's crust. The sea drained, dried, was replaced in turn by shoreline beaches and dunes, coal swamps, river floodplains, and vast alluvial fans of debris from the rising Rocky Mountains. Unimaginable tons of rock encased the long-forgotten mosasaur. Heated ground water, rich in dissolved minerals, ate away at the organic remains. Soft tissues vanished. Bones and teeth and scales resisted, but eventually they too succumbed, replaced cell by cell with silica and other more exotic minerals. The mosasaur's skeleton was petrified, literally turned to stone.

Far above, the world of the mosasaur and the dinosaur was ending. Evidence is strong that it was a terrible, instant end – a fireball from space, an impact on the shallow seabed on the northeast shore of Yucatan in Mexico, a searing flash of heat far beyond any nuclear blast mankind has ever imagined. From a crater over one hundred miles across, tsunami waves half a mile high ravaged the southern coast of North America, sweeping inland halfway across Texas. The incandescent heat ignited forests, turning the land that wasn't drowned into infernos. Hyper-hurricane winds screamed out from the glowing ruin of the crater, blasting and spreading fire in a widening circle of horror, consuming all life. The rolling hills, forests and river valleys of Pagosa died about four minutes after the impact in Mexico; by eight minutes, the blast wave tore across Canada. In one day, 65 million years ago, 200 million years of dinosaur rule came to an end.

Some forty percent of the planet's land biomass burned on that frightful day, probably a day in the springtime, judging from the abundant pollen found in the blast layer. Continent-wide forest fires raged. Animals that had been sheltered by mountains, deep valleys, and caves, peered out at the devastation, gasping desperately as the fires ate up the oxygen in the air. From the burning hole in Yucatan, steam and molten rock gushed upward, and a cloud of blackness spread from the wound.

How long did it last, this festival of destruction? We can't say – fortunately, nothing like this has happened as long as humans have been around. Computer models and educated estimates say that the world was shrouded in a cloud layer, unbroken and impenetrable, for one to ten years. No light reached the surface. The land froze, the seas cooled. Photosynthesis stopped, and the remaining plants died. Sea life, mostly unhurt by the impact itself, began to suffer. The atmosphere was depleted, its oxygen stolen by the worldwide fires, and there was no sunlight to fuel the plants in the sea to replace it. Cold, stagnant, its surface scummed by falling ash and soot and floating masses of rotting plants and animals, the sea began to die.

The great reptiles of the water world died with it. They were air breathers, and the air was fouled and toxic. Down along the food chain, death spiraled, killing the ammonites, the belemnites… The air was empty of the flying reptiles. They, too, had perished in the blast, the fires, the unbreathable air.

Yet the earth was not dead. Although the terrible center of the impact crater burned and erupted for decades, the rest of the planet recovered. The air gradually cleared, sunlight broke through, warmed the frozen wreckage of the forests and swamps and deserts. Seeds, buried in ash, sprouted. Spores grew into ferns and molds and mushrooms. Rare islands of life survived the devastation and cold. Animals crept forth, those lucky ones who had insulating fur and feathers, or could hibernate, or sleep away the years buried in cold mud – the small, the mobile, the ones who needed less food to live on and could breathe the thinner, oxygen-starved air.

So they inherited the ravaged world. The dinosaurs, the giant reptiles of the air and sea, were gone. Mammals and birds and fish were the new tenants of earth. They swarmed across the land, filled the sea and sky. They would never be as large as the great monsters of the past; the air has not yet, even today, recovered enough of its lost oxygen to fuel such huge beasts. But they thrived in the harsher world and made it their own.

Deep, buried, the ancient mosasaur lay, as the world above changed. The Colorado Plateau continued to rise, and water tore away the rocks grain by grain, washing them down the swollen rivers of the Southwest. The glaciers came, grinding up mountains, releasing vast floods of melt water to further scour the land. And, finally, only about a thousand years ago, the tireless forces of erosion opened the tomb of the poor mosasaur.

For a short time, the entire skeleton was probably exposed, as the soft shale of the ocean bottom wore away. But this was before the time of scientists. Indians may have seen this thing and wondered, maybe collected a shiny black tooth for a medicine bag or necklace. But time does not wait. The mosasaur's petrified bones mixed into the thin soil, broke apart under the stress of heat and cold and the acid of plant roots and rainfall. Many bones and teeth washed down and were carried away by streams. Only a few fragments remained in the crumbling hilltop rock, to be found in 1985, some 80 million years old now. Jawbones, ribs, teeth, flipper bones, vertebrae… these are a testament to a magnificent creature unlike anything now alive.

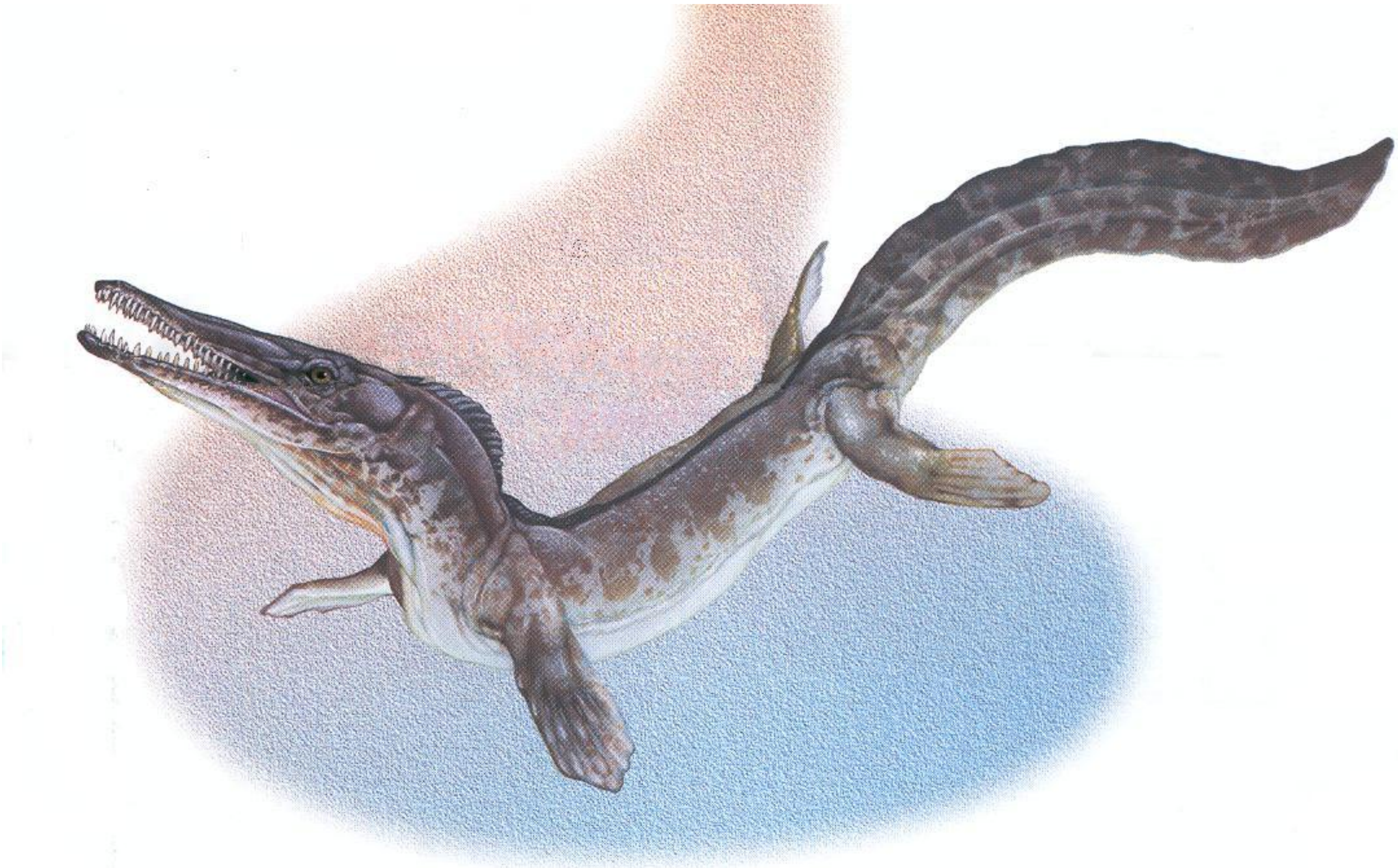


Figure 1: Artist's recreation of a mosasaur (Prognathodon overtoni) *like the specimen found in the Lewis Shale near the Valle Seco Road south of Pagosa Springs. Fragments of the skull, vertebrae, ribs, flippers, and tail are present in the soil, showing that a nearly complete skeleton must once have been buried there. This was an adult creature, a sea-going reptile at the top of the food chain, cruising the ancient ocean that once covered Southwest Colorado. The animal was about 35 feet long when it died and settled to the bottom of the shallow sea. It was buried by the gently settling clay and mud which became the Lewis Shale.*

Image courtesy of USDA Forest Service

Ophiomorpha Fossil Burrows

Ophiomorpha burrows are properly identified as "ichnofossils" or trace fossils, which means they are traces of past creatures, such as footprints, burrows, or tail-drag marks, rather than actual fossils of the creature itself. Ophiomorpha is the name given to a species of burrowing shrimp. The creature itself has not been found in the rocks here; only its burrows are known. These are distinctive trace fossils, running both horizontally and vertically, often branching and combining, typically found in sandstones of Permian (290 million years ago) to late Cretaceous age (the dinosaur era, ending 65 million years ago. The burrows are generally from ½ to 1 inch across, and can run for several feet. They almost always have a knobby outer surface, usually colored rusty brown to black, and sometimes have a rusty brown to shiny black core or filling, which can be separated from the burrow wall. This core can resemble a small, burned corncob, but is made of iron-cemented sand and silt that filled the original burrow.

Ophiomorpha is the scientific name; in English it means "snake-shaped", which describes the long, winding and branching burrows and their knobby corncob or "snakeskin" rind. By comparing the burrows of the vanished animal to those of similar creatures today (burrowing shrimp abut 1 inch long who build identical burrows worldwide), we can deduce that Ophiomorpha lived in shallow seashore and tidal beach zones. It probably stabilized its knobby burrow walls with pellets of sand cemented by mucus, and foraged for prey or scavenged dead organisms washing across the sandy bottom of its beachfront home. The top of the burrow was probably a small cone like a tiny volcano, but these superstructures have not been preserved as fossils due to the destructive nature of tidal zones.

Ophiomorpha burrows are very common in the "slick-rock" sandstone ledges of the upper mesa at the Chimney Rock Archaeological Area.

Figure 1: Ophiomorpha *fossils can be collected from public lands; however, because the sandstones containing these fossils may be part of an ancient cultural site, it is best to check with the local land management office before disturbing any area for fossil collecting.*

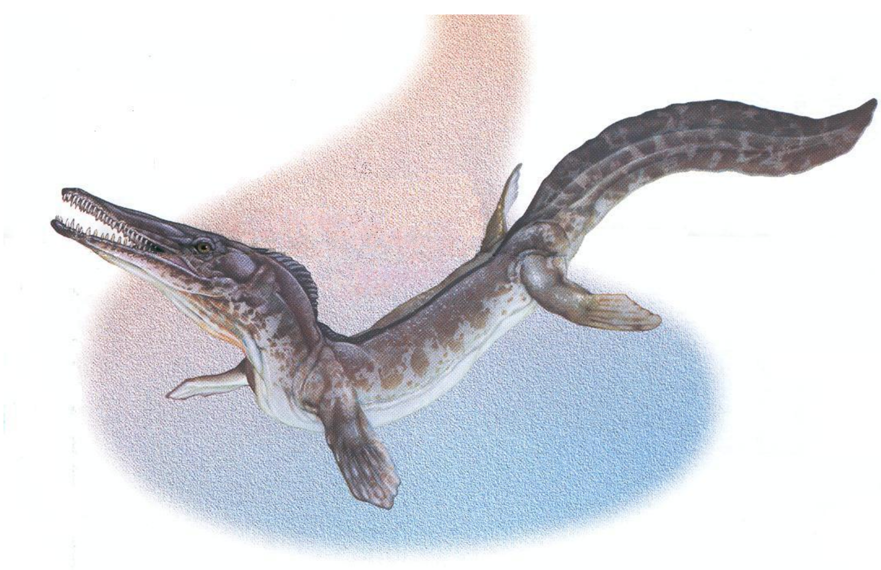
Photograph by Larry Larason

Pagosa Country Geologic History: *Geologic Road Log*

Compiled by Glenn Raby, Pagosa Ranger District/Field Office (retired) & Ed Stearns, Phillips Petroleum Company (retired)
Pagosa Springs, Colorado

Geology is the study of the Earth's rocks, minerals, structure and processes. The first real geological science was organized in the middle 1800's in England, Scotland, and Europe as an attempt to understand how mineral deposits formed and why the modern landscape looked the way it did. The first geologists faced some difficult questions. Why did some rocks cut cleanly across other rocks? Have volcanos, earthquakes, and erosion always worked at the same rate, or have they changed with time? How long does it take to build a mountain and to wear it away? Why do we find remains of plants and animals that have turned to stone, and are encased in rock? Why do we find sea-floor creatures fossilized at the tops on mountains and in the deepest deserts where water never flows? How old is the Earth? Many of geology's questions are still unanswered, but geologists have begun to understand the broad outline of the Earth's structure and how it has produced the rocks and minerals we see today. In the Pagosa Springs area, we can see a small part of that complex and beautiful machine that is our world. This field trip will cover only a short piece of geologic time, from the Dakota Sandstone to the sediments being laid down today - a trip of about 100 million years. As long as this seems, it is only about 2 percent of the earth's estimated 4.6 billion-year age. Yet it spans the death of the dinosaurs, the rise of the mammals, the birth of the Rocky Mountains, and the age of Mankind.

This paper is designed as a self-guiding road trip. The road log below lists **total trip mileage**. It begins at the Pagosa Springs Town Park at Hermosa Street and Hot Springs Boulevard and follows US Highway 160 from Pagosa Springs to the Overlook below Wolf Creek Pass. Driving directions are written in **BOLD LETTERS**. It helps to read ahead before you arrive at a stop or point of interest. Highway 160 is a busy road, so be careful and considerate. The accompanying map shows the local features and the major geological formations along the trip route. The map symbols, such as **Kmv**, refer to the geological formations described in the road trip log. A large-scale geological map of this part of Southwest Colorado is available from the United States Geological Survey in Denver or on the internet (Steven, T.A., Lipman, P.W., Hail, W.J., Jr., Barker, Fred, and Luedke, R.G., 1974, Geologic map of the Durango quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-764, scale 1:250,000). The chapter **Pagosa Country Geologic History: the Table** includes a detailed outline through time of Pagosa's geology and list of references.



Artist's recreation of a mosasaur (Prognathodon overtoni) like the specimen found in the Lewis Shale near the Valle Seco Road south of Pagosa Springs. Fragments of the skull, vertebrae, ribs, flippers, and tail are present in the soil, showing that a nearly complete skeleton must have once been buried there. This was an adult creature, a sea-going reptile at the top of the food chain, cruising the ancient ocean that once covered Southwest Colorado. The animal was about 35 feet long when it died and settled to the bottom of the shallow sea. It was buried by the gently settling clay and mud that became the Lewis Shale.

Image courtesy of USDA Forest Service

PAGOSA COUNTRY GEOLOGIC HISTORY - ROAD TRIP LOG

Miles	Points of Interest and Driving Instructions
0	**OPTIONAL STOP -** Park at the rear of the Spring Inn at the Pagosa Hot Springs sign. This is the main pool of the Great Pagosa Hot Springs, with water at nearly 180 degrees. The spring is fed by surface water that sinks into the ground along fissures, is heated by the hot rock below, and rises through the throat of the main pool. This plumbing system is quite complex and includes numerous other smaller springs and seeps, and may extend many miles across the land and many hundreds of feet in depth. The high mineral content of the water comes from the rocks below (Dakota Sandstone and Mancos Shale). The central pool lies atop a broad, low mound made of tufa or travertine (a type of limestone) deposited over thousands of years as mineralized water spilled from the pool and cooled, leaving a thin layer of minerals behind. Although the spring is located within rocks that are 70 to 80 million years old, it is one of the youngest geologic features here. Hot springs do not generally last very long in the geological record -- their heat sources die, their plumbing systems clog, their water sources dry up. The Pagosa Hot Springs may have started its life as a geyser, and it is now in its old age. It will probably fade away in the next fifty thousand years or so. Eventually, erosion, dissolution by rainwater and snowmelt, and the San Juan River will wear away the layers of travertine, and the springs will vanish forever. In geological terms, nothing is eternal. **RETURN TO TOWN PARK** Set your trip odometer at 0. Depart from Town Park. At the intersection of Hermosa Sreet and Hot Springs Boulevard, turn right on Hot Springs Boulevard and drive to the traffic light at US Highway 160.
0.1 Map symbol **Kml**	**TURN RIGHT (EAST) ON US 160** The accompanying map shows the geologic formations exposed along the trip route, using standard geologic map colors and symbols (such as **Kml**). These symbols are shown in the mileage column to the left, to help you connect the trip log with the geology on the map and on the ground. The heavy lines on the map outline the area where each rock type is exposed. The symbol **Kml** means **Cretaceous** (the geologic age of the sediment) and **Lower Mancos Shale** (the geologic formation or material). This format is followed through the trip log below. The highway crosses a landscape of Mancos Shale. The Mancos Shale is locally mapped as the lower (**Kml**) and upper (**Kmu**) shales. It weathers into soft rounded hills and dry, steep slopes, with poor soil development. It is made up of fine clay which makes wet-weather driving such an adventure. The dark gray color is from abundant carbon, the remains of plants and animals which died and settled to the ocean floor. The Mancos Shale was laid down in thin layers of fine mud as the Cretaceous Inland Sea widened and covered the old shoreline of the Dakota-Burro Canyon. The sea was about 300 feet deep and generally very quiet. Mud accumulated at the rate of 1 inch every thousand years, except for rare events when storms or floods on land flushed sand into the sea basin. The Mancos Shale is about 2,000 feet in maximum thickness, representing possibly 20 million years of slow deposition. In its dark layers can be found ammonites (coiled shells up to 3 feet across), fish scales and teeth, oyster and clam shells, and other fossils of vanished marine life. Continuing to the east, the highway follows the San Juan River, which has cut a wide channel between low cliffs of shale. These are nicely exposed behind the Junction Restaurant at the Highway 160-Highway 84 intersection.

1.0 **Kml**	<u>**OPTIONAL STOP - TURN RIGHT**</u> into the parking lot of the Junction Restaurant and drive to the back of the lot. This is an exposure of the upper Mancos Shale. It was deposited in the shallow Cretaceous age sea that covered this area some 90 million years ago. Many fossils, including clams, indicate that the sea was relatively shallow (200 to 300 feet deep) at times. The very thin, even layers show that the sea bottom was calm, with few burrowing animals to disturb the fine mud and clay that filtered down from above. The dark color comes from the carbon of millions of dead microscopic animals and plants; the decay of all this organic material robbed the bottom waters of their oxygen, leaving the lower sea water stagnant and dead. After the clay was cemented into rock, it was fractured and broken by later mountain-building to the north, and the fractures were filled by other minerals such as clear or white calcite and gypsum. <u>**RETURN TO HIGHWAY 160 AND TURN RIGHT. AT THE 160 – 84 JUNCTION, STAY ON 160 TOWARD WOLF CREEK PASS**</u> Ahead is the San Juan River valley and the spectacular San Juan Mountains beyond. The town of Pagosa Springs is built on Mancos Shale, eroded and carved by the river. The San Juan is a small river these days, but during the last glacial period (which ended some 18,000 years ago), it was a torrent of melt water and did some serious eroding. Most of the landforms we see today were the product of those years. Very little has happened in the geologically short time of the last 15,000 years.
6.0 **Kmv**	We are now leaving the Mancos Shale and climbing into the younger Mesaverde Formation (**Kmv**), several thin layers of terrestrial rock. Here the sequence is very thin, but further west it thickens and the Mesaverde is subdivided into separate formations, forming the impressive cliffs and tablelands of Mesa Verde National Park. The Mesaverde represents a brief shallowing of the ancient sea; about 90 million years ago, the Pagosa Springs area lay near the shoreline, with beaches and sand dunes, river channels and deltas, floodplains and swamps. The rocks deposited by these cycles of dry land, shoreline, and shallow sea include thin coal seams, sandstones, shales and mudstones, and tell the story of a short time when the sea retreated (called a **regression**); but eventually, the waters returned to flood Pagosa once more. All that can be seen from the highway is a short break in the shale cliffs, marked by low wooded hills.
6.5 **Kl**	We are now in the Lewis Shale, a thick sea-bed shale virtually identical to the older Mancos Shale. The area was submerged after the brief Mesaverde period, and the dark, fine mud of the sea bottom quietly accumulated again -- up to 2,400 feet thick in some areas. This was about 80 million years ago, and the sea persisted for perhaps another 10 to 20 million years. The Lewis Shale marks the last time that the Pagosa area was under a sea. As the end of the Cretaceous Period loomed, the western United States began to rise, lifted on upwelling magma from deep in the mantle of the Earth. Tectonic forces began to reshape the west, lifting the Colorado Plateau and sinking the Paradox, San Juan, and other great basins, over the next 40 million years. Mountain ranges composed of huge volcanos lay just in the future. The Lewis sea began to drain and fill; the shoreline advanced over the old mud and clay of the seafloor. Beaches and sand dunes and swamps and river systems replaced the quiet waters for the last time (so far!).

	The Lewis Shale has several thin limestone layers in its lower section; these weather out as rounded, discontinuous orange ledges. These are lime concretions, formed by crystallization of calcite (limestone) at the floor of the ancient ocean. Near the top of the Lewis are found thin sandstone beds, the result of floods and shoreline deposits that washed sand into the shallowing sea. Each of these thin beds probably represents one event, one instant in time.
7.0 **Ti**	**STOP 1 – LOOK FOR A GRAY ROCK CUT ALONG THE LEFT SIDE OF THE HIGHWAY. PARK OFF THE RIGHT SHOULDER OF HIGHWAY 160**, just past the San Juan River Village entrance. This is the Jackson Mountain Laccolith, an intrusion of magma into the Lewis Shale that caps Jackson Mountain. The magma was intruded during the Tertiary Period, probably around 10 million years ago. The highway crosses the edge of the intrusive body, called a laccolith because it resembles a shallow lake of magma enclosed in the older shale. Cross over to the westbound highway shoulder. **WATCH FOR TRAFFIC.** The intrusive rock is a dense gray andesite porphyry, a fine-grained igneous rock with large single crystals scattered throughout. The orange color of the weathered rock comes from the iron contained in its minerals. The porphyry contains crystals of clear quartz coated with a green mineral called chlorite, rectangular crystals of plagioclase feldspar which demonstrate chemical zoning (this is shown by a change in color from the center out to the edge of the crystal), patches of micropegmatite (coarse crystal mesh of quartz, mica, and feldspar), xenoliths (pieces of older rock torn loose and partly melted by the hot magma), and veins of milky quartz and calcite which filled later fractures in the igneous rock and contain copper and iron pyrite (fool's gold). Along the edges of the igneous intrusive, you can see the contact zone, where the hot magma actually baked the Lewis Shale into a hornfels (a natural form of ceramic, like clay pottery fired in a kiln). This rock is much harder than the Lewis Shale which surrounds it. Look for the drill holes and radial fractures that mark where the stone had to be blasted to widen the highway. Andesite is chemically similar to the mineral composition of the lower part of the Earth's crust, and probably results from partial melting of rock in the upper mantle below the crust, rising and mixing with the cooler rocks above. This rock tells a dramatic story. It began as liquid magma far underground, hot and under extreme pressure. The feldspar crystals began to form here, their cores rich in calcium. As the magma began to rise and lose heat and pressure, the growing feldspar's chemistry changed to more sodium-rich, causing the zoning you can see in the crystals. Quartz began to crystallize in its high-temperature form (beta-quartz), as the magma was intruded into the cool, wet Lewis Shale. Drastic losses in heat followed, and the magma began to freeze, rapidly crystallizing, stopping the growth of the large feldspar and quartz crystals. But the final tale is told by the beta-quartz and the odd frothy "bubble tracks" crisscrossing the rock. Still under high pressure but losing temperature, the magma body erupted, exploding onto the ancient surface. The immediate loss of pressure completed the 'freezing" of the magma, preventing the beta-quartz from changing into its more familiar prismatic crystal form, and freeing the trapped gasses in the magma- creating the "bubble tracks" as the gas escaped the cooling rock. Look for the small double-pyramid beta-quartz crystals in the rock, the sign of the last cooling of the adesite.

8.5	**CONTINUE NORTHEAST TOWARD WOLF CREEK PASS** The highway crosses an area where the land is sliding down toward the river – this is the Jackson Mountain Slide. **BE CAREFUL – THE HIGHWAY IS FREQUENTLY DAMAGED HERE.** The next stop is a road cut – look for a steep cliff on the left, with white sandstone and thin, darker layers of coal arching above the cliff. On the right is a wide flat area where you will park.
9.2 **Kkp**	**STOP 2 – PARK ON RIGHT SIDE OF HIGHWAY** and cross to the other side along the cut slope. **WATCH FOR TRAFFIC.** This is an exposure of the Pictured Cliffs Sandstone and the overlying Fruitland Formation **(Kkp)**. The Cretaceous sea was drying up for the last time. Tidal flats and beach dunes spread over the sea-floor shales, and were in turn buried by river sands and the thick vegetation of swamps and floodplain forests. The land was again rising, and the sands of the river and shoreline (the Pictured Cliffs Sandstone) were being rapidly buried; many feet of saturated sand and silt might be dumped in a single flood. The weight of this material pressing down on the sand below caused a process called soft-sediment deformation, which produced a sandstone "volcano" -- the heavier, wet sands above sank and forced up the lighter material below into a convoluted dome, deforming the coal seams above as you can see in the road cut. These structures are generally small and rarely preserved. The very large size of this "volcano" may be the result of seismic shock from the asteroid impact at Chixulub in the Yucatan that caused the extinctions of some 75% of all life forms, including the dinosaurs and great sea and air reptiles, at the end of the Cretaceous Period. **CONTINUE ON HIGHWAY 160.**
10.3	This part of the road passes through the Kirtland Shale, a thin sandy shale laid down when the Cretaceous inland sea made an attempt to flood its former bed and no generally mapped here. But mountains were already rising to the north and east, first as broad domes of the older sedimentary rock, then in violent volcanic upheavals. Tremendous amounts of sediment and volcanic rock were swept into the shallow basin, choking the sea and building new land. The Cretaceous sea was gone, and the Cretaceous Period was close to its end. The Pagosa area was still dominated by dinosaurs, though -- their bones occur as fossils throughout the rocks, but their time was almost over.
10.5	We are now in the Animas Formation, a thick pile of river deposits made up of sand, gravel, mud, and volcanic rock washed down from the rising mountains. This was 65 million years ago, and one of the most important geological events of the earth's history occurred: the dinosaurs, along with come 70 percent of all life forms, died out. Among the survivors: birds, small reptiles -- and the mammals. This rock layer may contain the boundary between the Mesozoic Era, the Age of the Dinosaurs, and the Cenozoic Era, the Age of the Mammals, but it has not been definitely identified here. This is the youngest sedimentary formation which we will see on this trip, and it is not shown on the geologic map because there is very little of it exposed here. We are now approaching the skirts of the volcanos that built the San Juan Mountains and covered the sedimentary rocks under thousands of feet of ash, lava, and pumice.
14.0 **Qa**	We are crossing glacial debris which forms the valley floor; it was washed down from the surrounding mountains during the most recent Ice Age which ended some 12,000 to 15,000 years ago. This material is too young to have been cemented into rock. The West Fork of the San Juan River valley to the left of the highway is a glaciated valley, U-shaped with a flat bottom and steep sides.

18.0 **Tev**	**STOP 3 - TURN LEFT INTO THE OVERLOOK PARKING LOT** This is the last stop of the tour, and a view of the last major geologic activity of the area - the San Juan Volcanic Field. The last 30 million years have seen almost continuous eruption and volcanic mountain-building throughout the San Juan Mountains. The Jackson Mountain Laccolith (Stop 3) is one minor part of this process. The rocks surrounding the Overlook are volcanic in origin. The well-cemented agglomerates (formed by erosion and reworking of volcanic debris) are resistant to erosion, forming the spectacular cliffs and spires; the softer conglomerates (formed by ash and debris flows, eruptions, and superheated avalanches) erode quickly and form the slopes below. Some of the volcanic rock was melted, or welded, together by its own intense heat, forming welded tuffs and obsidian beds. Huge stratovolcanos rose, exploded and laid waste to hundreds of square miles, and collapsed into yawning calderas, only to have new volcanos rise from their ruins. Recent studies (1996) show that some of the largest and most powerful eruptions on the planet occurred here. The La Garita Caldera eruption pulverized some 1,500 cubic miles of rock, with a force equal to 10,000 times that of the eruption of Mount St. Helens, creating a crater complex that stretches from Pagosa Springs to near Alamosa, almost 70 miles across. That single eruption must surely have killed every living thing in the entire Four Corners region. Only in the last 4 million years has this area been quiet; as the volcanic activity faded, the last magma squeezed into faults to form the local dikes and laccoliths. Erosion softened the jagged volcanic mountains, and life returned to the land. Hot springs and geysers were abundant as water from rain and snow met the cooling underground pockets of magma. Between 1 million and 18,000 years ago, glaciers grew and melted, carving deep valleys and bulldozing vast amounts of shattered rock into the river channels which carried away their floods of meltwater. When the last glaciers retreated, they left behind canyon walls too steep to support themselves; without the half-mile deep masses of ice to hold them up, they collapsed in landslides and mudflows that continue to this day.

Pagosa Country Geologic History: *Simplified Geologic Map*

Pagosa Country Geologic Map

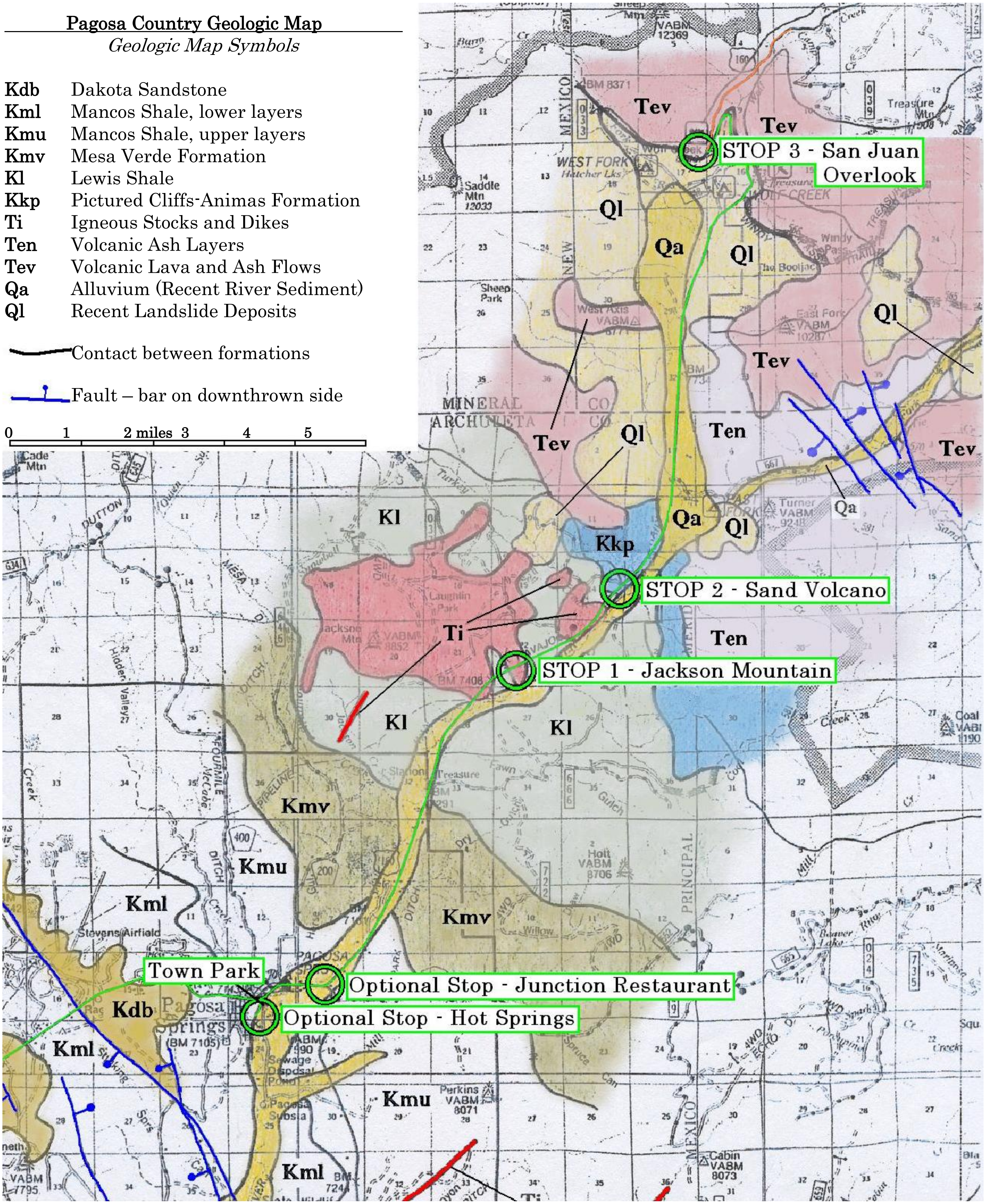
Geologic Map Symbols

Kdb	Dakota Sandstone
Kml	Mancos Shale, lower layers
Kmu	Mancos Shale, upper layers
Kmv	Mesa Verde Formation
Kl	Lewis Shale
Kkp	Pictured Cliffs-Animas Formation
Ti	Igneous Stocks and Dikes
Ten	Volcanic Ash Layers
Tev	Volcanic Lava and Ash Flows
Qa	Alluvium (Recent River Sediment)
Ql	Recent Landslide Deposits

Contact between formations

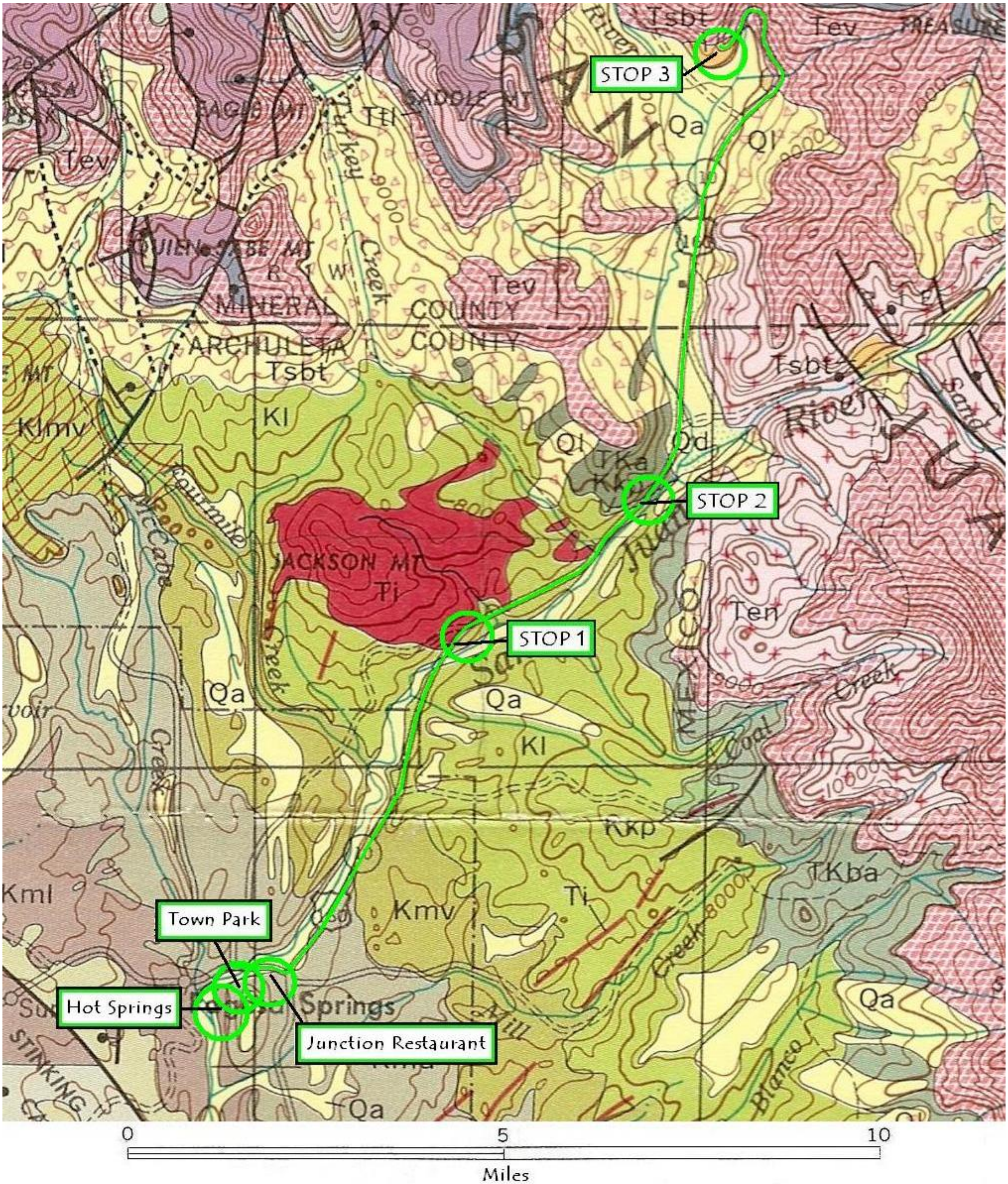
Fault – bar on downthrown side

0 1 2 miles 3 4 5



Pagosa Country Geologic History: *Geologic Map*

From Steven and others, 1974



Contour interval 200 feet. See geologic map key at end of document.

East Fork Fire, Ice and Landslide: *Geologic Road Log*

Compiled by Glenn Raby, Pagosa Ranger District/Field Office (retired) & Ed Stearns, Phillips Petroleum Company (retired)
Pagosa Springs, Colorado

EAST FORK LANDSLIDE: In May 2008, a portion of the slope just before the Sand Creek drainage failed, rupturing the natural gas pipeline and destroying the East Fork Road. The location of the landslide is between Stop 3 and Stop 4 in this Road Log at about Mile 13.6. The detailed description of the landslide and its geologic characteristics are included in a special section of the Road Log following Stop 3 and in attachments following the Road Log Geologic Maps. Contact the Pagosa Ranger District Office for current road information. The following Road Log can be followed when regular vehicle traffic is permitted.

The geology of the East Fork Valley is a study in the processes that formed the Earth and shaped the landscape. This paper is designed as a self-guiding road trip. The road log below lists **total trip mileage**. It begins at the Pagosa Springs Town Park at Hermosa Street and Hot Springs Boulevard and follows US Highway 160 from Pagosa Springs to the East Fork Road and ends at Silver Falls. Driving directions are written in **BOLD LETTERS**. It helps to read ahead before you arrive at a stop or point of interest. Highway 160 is a busy road, so be careful and considerate. The attached map shows the roads and features noted in the Log. **NOTE - THE ROAD REQUIRES HIGH CLEARANCE VEHICLES FOR THE COMPLETE TRIP.** Standard passenger vehicles may not be able to cross some of the stream fords and rough stretches of roadway. Always watch for falling rock and be aware of other vehicles using the road. The accompanying map shows the local features and the major geological formations along the trip route. The map symbols, such as **Kmv**, refer to the geological formations described in the road trip log. A large-scale geological map of this part of Southwest Colorado is available from the United States Geological Survey in Denver or on the internet (Steven, T.A., Lipman, P.W., Hail, W.J., Jr., Barker, Fred, and Luedke, R.G., 1974, Geologic map of the Durango quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-764, scale 1:250,000). The chapter **Pagosa Country Geologic History: the Table** includes a detailed outline through time of Pagosa's geology and list of references.

Pagosa Springs sits in the valley of the San Juan River, on a landscape of Cretaceous-age sedimentary rock -- the ocean-bottom mud of the Lewis Shale. During the last years of the Dinosaur Age, some 80 to 100 million years ago, the shallow sea which covered western North America drained away. A series of river deltas, floodplains, and swamps covered this area. The age of the dinosaurs ended 65 million years ago, apparently in a single instant of climate change and cataclysm. No one knows for sure what ended the 200 million year reign of these great beasts, but their disappearance opened the world for the mammals. As the modern Rocky Mountains rose to the north, this flat, wet landscape with its entombed dinosaur bones was buried by debris washed down from those new mountains; at the same time, immense volcanic forces began to rip and shatter the land.

The East Fork of the San Juan River begins high in the volcanic mountains of the Continental Divide. The valley of the East Fork ranges in elevation from 7,600 feet at its mouth (where it enters the main San Juan River valley along Highway 160) to over 9,000 feet, with the surrounding mountain peaks topping 13,000 feet. The road trip log ends at the Silver Falls Guard Station, an historic Forest Service ranger station now rented to visitors, at 8,300 feet elevation. A short hike along the trail just east of the cabin takes you to Silver Falls, a classic example of a hanging valley left behind when the glaciers retreated for the last time. The mountains of the Continental Divide are remnants of a mighty range of volcanos that formed between 40 million and 10 million years ago. After the last eruptions, the volcanic peaks, which may have been as high as 20,000 feet, were swiftly eroded to the level we see today.

Starting about 100,000 years ago, the Earth entered the most recent of a series of glacial periods we call the Ice Age. This period is known to geologists as the Wisconsin Glaciation, and the last retreat of the ice was sometime between 18,000 and 12,000 years ago. The Ice Age itself has not actually ended; interglacial periods are common and we are still in such a period between the advance and retreat of glaciers. How long it may be until the next advance of the ice, no one can predict.

For the East Fork Valley, the Wisconsin Glaciation was a significant event. Flowing down from the still-lofty volcanic mountains was a river of ice called the San Juan Glacier. At its height, it may have been 2,000 feet thick, and it flowed for an estimated 50,000 years - longer by far than humans have inhabited the Americas. All of recorded human history has only happened since the last remnants of the glacier melted away; the San Juan ice sheet predates all the great civilizations of mankind. Prehistoric Indians may have seen the last, shrunken tongues of ice, high among the mountain peaks. Archaeological finds along the Continental Divide in 1997 show that people were hunting in those wildernesses when the glacier was in its final retreat. What must they have thought on seeing these rivers of ice? Could they have dreamed of the glacier at its greatest extent? Imagine for yourself the spectacle of a stream of ice and rock, 7 miles long, over a mile wide, filling the entire East Fork Valley - almost 3 cubic miles of solid ice, weighing something like 11 billion tons, fed by many smaller glaciers from the higher peaks and scarps above.

This incredible mass of ice was moving, slowly but with inconceivable power, and as it moved, it ground away at the walls and floor of the valley, scouring the soft volcanic ash and lava beds. A moving mountain of broken rock and sand and gravel and clay was picked up and transported by the glacier, to be dumped along the edges and at the toe of the ice sheet, in walls and mounds called moraines. Along its hidden base, the ice melted and water ran in ice-tunnelled rivers, laying down beds of sediment, left behind on the valley floor when the ice was gone. These sinuous layers of river sand and gravel are called eskers, and the East Fork Valley floor must once have been thick with them. With each advance and retreat of the ice over thousands of years, a deep carpet of such shattered rock and sediment was laid down. When the glacier at last retreated high into the mountains, its flooding melt waters reworked this material, called glacial till, into thick alluvial soil. The exposed walls of the valley, finally clear of ice, rose in the characteristic U-shaped profile of a glaciated valley; further down, below the reach of the glacier, the river cut the V-shaped canyon which gives entrance to the East Fork Valley.

The nearly vertical cliffs of the post-glacial valley, however, were not stable. The volcanic rock was too soft and porous to hold up such steep walls. Over the last 12,000 years, the walls have been collapsing in a series of rockfall, landslides, and mud flows, so that the edges of the valley now rise into scenic rolling hills, covered by stands of aspen trees which love disturbed or moving ground. The East Fork, clogged with tremendous amounts of this debris, wallows across the wide valley in a branching pattern called a braided stream, alternately flooding and dying out, unable to flush out the massive layer of sediment in its channels. Recent work has been done to stabilize the banks and confine the river to a single channel, returning it to a stream pattern known as meandering. This work is experimental and it will take many years before we see if the river has been convinced to change its ways.

What of the future of the East Fork Valley? Predictive geology is not yet a reliable science, but some things are relatively certain. Erosion will continue to wear away the cliffs and slopes of the valley walls, and the river will continue to carry away the debris. Over the next 50,000 years, the valley will become lower and broader, and the river will remain its central feature. Once the glacier returns, the cycle begins again, and the valley we and our descendents enjoy will no longer exist. The domain of the ice is a temporary one, though, and sometime in the distant future there will again be a valley here, filled with a beautiful river, bounded by spectacular cliffs and forests, rich in life and variety. This has happened many times before, and in the long life of our Earth, it is not likely to be the last time for the East Fork Valley.

EAST FORK FIRE, ICE AND LANDSLIDE - ROAD TRIP LOG

Miles	Points of Interest and Driving Instructions
0	**OPTIONAL STOP -** Park at the rear of the Spring Inn at the Pagosa Hot Springs sign. This is the main pool of the Great Pagosa Hot Springs, with water at nearly 180 degrees. The spring is fed by surface water that sinks into the ground along fissures, is heated by the hot rock below, and rises through the throat of the main pool. This plumbing system is quite complex and includes numerous other smaller springs and seeps, and may extend many miles across the land and many hundreds of feet in depth. The high mineral content of the water comes from the rocks below (Dakota Sandstone and Mancos Shale). The central pool lies atop a broad, low mound made of tufa or travertine (a type of limestone) deposited over thousands of years as mineralized water spilled from the pool and cooled, leaving a thin layer of minerals behind. Although the spring is located within rocks that are 70 to 80 million years old, it is one of the youngest geologic features here. Hot springs do not generally last very long in the geological record -- their heat sources die, their plumbing systems clog, their water sources dry up. The Pagosa Hot Springs may have started its life as a geyser, and it is now in its old age. It will probably fade away in the next fifty thousand years or so. Eventually, erosion, dissolution by rainwater and snowmelt, and the San Juan River will wear away the layers of travertine, and the springs will vanish forever. In geological terms, nothing is eternal. **RETURN TO TOWN PARK** Set your trip odometer at 0. Depart from Town Park. At the intersection of Hermosa Sreet and Hot Springs Boulevard, turn right on Hot Springs Boulevard and drive to the traffic light at US Highway 160.
0.1 Kml	**TURN RIGHT (EAST) ON US 160** The accompanying map shows the geologic formations exposed along the trip route, using standard geologic map colors and symbols (such as **Kml**). These symbols are shown in the mileage column to the left, to help you connect the trip log with the geology on the map and on the ground. The heavy lines on the map outline the area where each rock type is exposed. The symbol **Kml** means **Cretaceous** (the geologic age of the sediment) and **Lower Mancos Shale** (the geologic formation or material). This format is followed through the trip log below. The highway crosses a landscape of Mancos Shale. The Mancos Shale is locally mapped as the lower (**Kml**) and upper (**Kmu**) shales. It weathers into soft rounded hills and dry, steep slopes, with poor soil development. It is made up of fine clay which makes wet-weather driving such an adventure. The dark gray color is from abundant carbon, the remains of plants and animals which died and settled to the ocean floor. The Mancos Shale was laid down in thin layers of fine mud as the Cretaceous Inland Sea widened and covered the old shoreline of the Dakota-Burro Canyon. The sea was about 300 feet deep and generally very quiet. Mud accumulated at the rate of 1 inch every thousand years, except for rare events when storms or floods on land flushed sand into the sea basin. The Mancos Shale is about 2,000 feet in maximum thickness, representing possibly 20 million years of slow deposition. In its dark layers can be found ammonites (coiled shells up to 3 feet across), fish scales and teeth, oyster and clam shells, and other fossils of vanished marine life. Continuing to the east, the highway follows the San Juan River, which has cut a wide channel between low cliffs of shale. These are nicely exposed behind the Junction Restaurant at the Highway 160-Highway 84 intersection.

1.0 **Kml**	<u>OPTIONAL STOP - TURN RIGHT</u> into the parking lot of the Junction Restaurant and drive to the back of the lot. This is an exposure of the upper Mancos Shale. It was deposited in the shallow Cretaceous age sea that covered this area some 90 million years ago. Many fossils, including clams, indicate that the sea was relatively shallow (200 to 300 feet deep) at times. The very thin, even layers show that the sea bottom was calm, with few burrowing animals to disturb the fine mud and clay that filtered down from above. The dark color comes from the carbon of millions of dead microscopic animals and plants; the decay of all this organic material robbed the bottom waters of their oxygen, leaving the lower sea water stagnant and dead. After the clay was cemented into rock, it was fractured and broken by later mountain-building to the north, and the fractures were filled by other minerals such as clear or white calcite and gypsum. **<u>RETURN TO HIGHWAY 160 AND TURN RIGHT. AT THE 160 – 84 JUNCTION, STAY ON 160 TOWARD WOLF CREEK PASS</u>** Ahead is the San Juan River valley and the spectacular San Juan Mountains beyond. The town of Pagosa Springs is built on Mancos Shale, eroded and carved by the river. The San Juan is a small river these days, but during the last glacial period (which ended some 18,000 years ago), it was a torrent of melt water and did some serious eroding. Most of the landforms we see today were the product of those years. Very little has happened in the geologically short time of the last 15,000 years.
5.5 **Qa**	The bridge crosses the San Juan River, which drains the East Fork Valley. Much of the sediment in the river bottom is glacial till (debris) from the glaciers in the upper East Fork, originally deposited as moraines. Lateral moraines run alongside the glacier as it flows, and terminal moraines form as dams at the lower end of the glacier. These terminal moraine dams can cause lakes of meltwater to form, and when the dams eventually break, huge floods run down the valley below. This must have happened many times over the thousands of years of life of the San Juan Glacier. As the glacier finally melted, its meltwater reworked the glacial debris into a type of sediment called alluvium, meaning water-deposited sediment. The accompanying map shows the general geologic formations exposed along the trip route, using standard geologic map symbols (such as **Qa**). These symbols are shown in the mileage column to the left, to help you connect the trip log with the geology on the map and on the ground. The heavy lines on the map outline the area where each rock type is exposed. The symbol **Qa** means **Quaternary** (the geologic age of the sediment) and **alluvium** (the geologic formation or material). This format is followed through the trip log below.
6.0 **Kmv**	We are now leaving the Mancos Shale and climbing into the younger Mesaverde Formation (**Kmv**), several thin layers of terrestrial rock. Here the sequence is very thin, but further west it thickens and the Mesaverde is subdivided into separate formations, forming the impressive cliffs and tablelands of Mesa Verde National Park. The Mesaverde represents a brief shallowing of the ancient sea; about 90 million years ago, the Pagosa Springs area lay near the shoreline, with beaches and sand dunes, river channels and deltas, floodplains and swamps. The rocks deposited by these cycles of dry land, shoreline, and shallow sea include thin coal seams, sandstones, shales and mudstones, and tell the story of a short time when the sea retreated (called a **regression**); but eventually, the waters returned to flood Pagosa once more. All that can be seen from the highway is a short break in the shale cliffs, marked by low wooded hills.

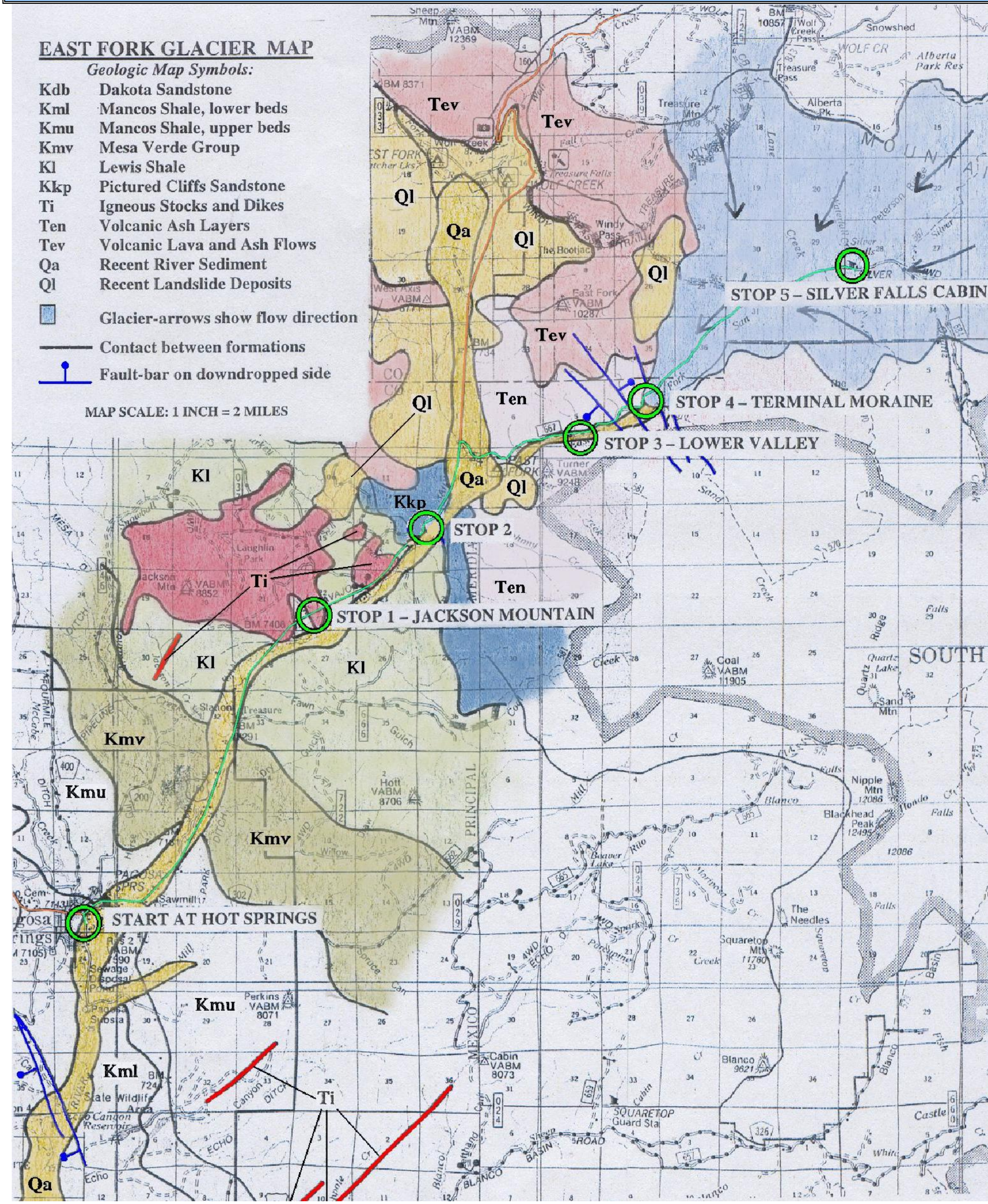
6.5 **Kl**	We are now in the Lewis Shale, a thick sea-bed shale virtually identical to the older Mancos Shale. The area was submerged after the brief Mesaverde period, and the dark, fine mud of the sea bottom quietly accumulated again -- up to 2,400 feet thick in some areas. This was about 80 million years ago, and the sea persisted for perhaps another 10 to 20 million years. The Lewis Shale marks the last time that the Pagosa area was under a sea. As the end of the Cretaceous Period loomed, the western United States began to rise, lifted on upwelling magma from deep in the mantle of the Earth. Tectonic forces began to reshape the west, lifting the Colorado Plateau and sinking the Paradox, San Juan, and other great basins, over the next 40 million years. Mountain ranges composed of huge volcanos lay just in the future. The Lewis sea began to drain and fill; the shoreline advanced over the old mud and clay of the seafloor. Beaches and sand dunes and swamps and river systems replaced the quiet waters for the last time (so far!).
7.0 **Ti** **Kl**	**<u>STOP 1 - PARK ON THE RIGHT SIDE OF THE HIGHWAY - WATCH FOR TRAFFIC!</u>** Just north of the San Juan River Village on the west (left) side of the road, is an igneous outcrop in the road cut. This is a Tertiary intrusive (Ti), about 25 to 30 million years old. It is a rock type called andesite porphyry; the fresh rock is gray, but it weathers to the dull orange seen above the gray core. This was once molten material, which forced its way between the layers of the sedimentary Lewis Shale, and cooled as the Jackson Mountain laccolith, a lake-shaped body of igneous rock. Andesite is a classification of fine-grained igneous rock, and porphyry means that it has large individual crystals in a fine-grained matrix. The large crystals are called phenocrysts. There are double hexagonal pyramids of beta-quartz, a high-temperature variety of common quartz. Phenocrysts of plagioclase feldspar show good rectangular crystal shape and internal color zoning, the result of changes in the chemical composition of the magma as it cooled and the crystals grew. Micropegmatites (pockets of coarse crystals) of feldspar, quartz, and amphibole are the result of cooling bubbles of element-enriched fluids, the last part of the magma to crystallize. Thin fissures and cracks are filled with calcite and quartz crystals, formed after the rock cooled and fractured. Small amounts of chalcopyrite and pyrite (copper and iron sulfides) occur throughout the rock. It is the iron in these minerals which gives the rock its orange rusty color as it weathers. Look along the edges of the main outcrop, and you will find the country rock, the geologic formation which surrounds the igneous intrusive. This is the Cretaceous age Lewis Shale (**Kl**) which has been baked into near-ceramic hardness by the heat of the intruding magma. This is an example of contact metamorphism, in which rock is chemically changed by heat and pressure. The Lewis Shale is about 71 to 80 million years old.
8.5	**<u>CONTINUE NORTHEAST TOWARD WOLF CREEK PASS</u>** The highway crosses an area where the land is sliding down toward the river – this is the Jackson Mountain Slide. **<u>BE CAREFUL – THE HIGHWAY IS FREQUENTLY DAMAGED HERE.</u>** The next stop is a road cut – look for a steep cliff on the left, with white sandstone and thin, darker layers of coal arching above the cliff. On the right is a wide flat area where you will park.

9.2 **Kkp**	<u>**STOP 2 – PARK ON RIGHT SIDE OF HIGHWAY**</u> and cross to the other side along the cut slope. <u>**WATCH FOR TRAFFIC.**</u> This is an exposure of the Pictured Cliffs Sandstone and the overlying Fruitland Formation. The Cretaceous sea was drying up for the last time. Tidal flats and beach dunes spread over the sea-floor shales, and were in turn buried by river sands and the thick vegetation of swamps and floodplain forests. The land was again rising, and the sands of the river and shoreline (the Pictured Cliffs Sandstone) were being rapidly buried; many feet of saturated sand and silt might be dumped in a single flood. The weight of this material pressing down on the sand below caused a process called soft-sediment deformation, which produced a sandstone "volcano" -- the heavier, wet sands above sank and forced up the lighter material below into a convoluted dome, deforming the coal seams above as you can see in the road cut. These structures are generally small and rarely preserved. The very large size of this "volcano" may be the result of seismic shock from the asteroid impact at Chixulub in the Yucatan that caused the extinctions of some 75% of all life forms, including the dinosaurs and great sea and air reptiles, at the end of the Cretaceous Period. <u>**CONTINUE ON HIGHWAY 160.**</u>
Km **Kmv** **Kl**	From the Town Park to this area, you have passed through, from older to younger, the Mancos Shale, Mesa Verde Group, Lewis Shale, Pictured Cliffs Sandstone, and Fruitland Formation as you drove along the highway. This is a series of sedimentary rock layers, representing periods when the area was sea floor (**Km -** Mancos Shale), briefly shoreline and beach (**Kmv -** Mesa Verde), sea floor again (**Kl** - Lewis Shale), shoreline beaches, dunes, peat bogs and coal swamps of the last retreat of the sea (**Kkp** - Pictured Cliffs Sandstone, Fruitland Formation), and finally the eroded debris from the young Rocky Mountains which buried the swamps -- the Animas Formation. The Animas Formation is a thick pile of river deposits made up of sand, gravel, mud, and volcanic rock washed down from the rising mountains. This was 65 million years ago, and one of the most important geological events of the earth's history occurred: the dinosaurs, along with come 70 percent of all life forms, died out. Among the survivors: birds, small reptiles -- and the mammals. This rock layer may contain the boundary between the Mesozoic Era, the Age of the Dinosaurs, and the Cenozoic Era, the Age of the Mammals, but it has not been definitely identified here. This is the youngest sedimentary formation which we will see on this trip, and it is not shown on the geologic map because there is very little of it exposed here. We are now approaching the skirts of the volcanos that built the San Juan Mountains and covered the sedimentary rocks under thousands of feet of ash, lava, and pumice.
10.4	<u>**TURN RIGHT ON EAST FORK ROAD IMMEDIATELY AFTER CROSSING THE BRIDGE**</u> This is a gravel road and is narrow, with blind curves - watch for traffic. To the left you can see the mountains of the Continental Divide, a string of volcanos which erupted up to about 10 million years ago. You are entering the San Juan National Forest, and the lower end of the narrow, V-shaped valley cut by the melting glacial water of the ancient East Fork River.
11.3 **Qa**	On the left are wire coffers to keep debris from sliding onto the road. The cobbles and gravel in the coffers are river deposits, washed down from glacial debris higher in the valley and smoothed by centuries of tumbling and polishing in the stream. This material formed during the Quaternary age and is called alluvium (**Qa**).

12.0 **Ten**	Here, the road passes through the narrowest part of the canyon. The walls were laid down in successive eruptions of Tertiary age eruptive deposits (Ten) (volcanic ash and tuff) and later reworked by streams (pyroclastic deposits). This rock is soft and easily erodes. Notice the talus slopes (slides of broken rock) lining the valley along the road and river channel. The San Juan Glacier did not come this far down the valley; the soft volcanic rock could never have withstood the cutting power of the ice. The heavily fractured, dark rock along the road cut is called dacite; it is made up of calcium-rich plagioclase feldspar crystals in a dark, iron- and magnesium-rich matrix. The plagioclase crystals show layering which indicates that this rock was a lava flow.
13.0 **Qa**	Crossing the East Fork River. The gravel and boulders come from glacial debris higher in the valley.
13.2	<u>STOP 3 - PARK IN THE PICNIC/CAMPING AREA</u> Walk out onto the meadow and review the geologic history of the valley from the first page.
13.4 **Ten**	Notice to the left, the thick white ash layers, and the colored layers of tuff and pyroclastic rock below. The colors come from minerals contained in the rock, dissolved and redeposited by ground water. This rock wall includes the Tuff of Crystal Lake (Silverton Caldera eruptive rock) and volcaniclastic layers (reworked volcanic deposits) above the multicored tuff beds, forming the more resistant ledges and layers.
13.6	<u>EAST FORK LANDSLIDE</u> Beginning on May 2, 2008, a narrow section of rock and earth at this location began sliding, eventually destroying the East Fork Road for a distance of about 1,000 feet and rupturing the adjacent natural gas pipeline. The landslide extends about 3,500 feet upslope to the south and terminates at the East Fork San Juan River. The slide initially threatened to dam the river with soil and rock as well as a number of mature conifer trees carried downslope with it. As of this writing, the river has managed to maintain its flow and has not been significantly blocked. The slide originated in volcanic rock mapped in 1985 as the Oligocene age (about 23.8 to 28 million years) Tuff of Crystal Lake, an eruptive ash-flow from the Silverton Caldera. This is one of at least 14 violent caldera eruptions which together form the San Juan Volcanic Field mapped in 1975 by Steven and others. Other landslides and slope failures originate in this volcanic formatin throughout the East Fork valley. The landslide at this site occurs in a broad area between two older and currently inactive faults (see the attached geologic map; the faults are between Stops 3 and 4). The faults are not assumed to have contributed to the landslide's origin. The area between the faults was mapped in 1985 as a potentially unstable slope, consisting of a complex of many large and small slope failures and slides. The most recent movement in this complex occurred sometime in the late 1970's and was minor in scope. In 2006, the pipeline was ruptured by stress in the same location as the present landslide, but no actual earth movement was seen. In early 2007 elevated strain levels were measured, but no damage occurred to the pipeline or the road. On May 2, 2008, the line ruptured and earth movement was seen, the start of the current slide. Measured movement of earth and trees averaged about 4 feet per day for the next few weeks. Since June of 2008, the slide has been monitored and there has been no significant further movement. Plans to reconstruct the road and provide a long-term repair to the current temporary pipeline are underway. Refer to the attached exhibits following the geologic maps at the end of this Road Log for more detailed information.
13.7	Crossing the river again. The valley is still narrow, steep-walled, and V-shaped - the characteristic shape of a valley cut by running water.

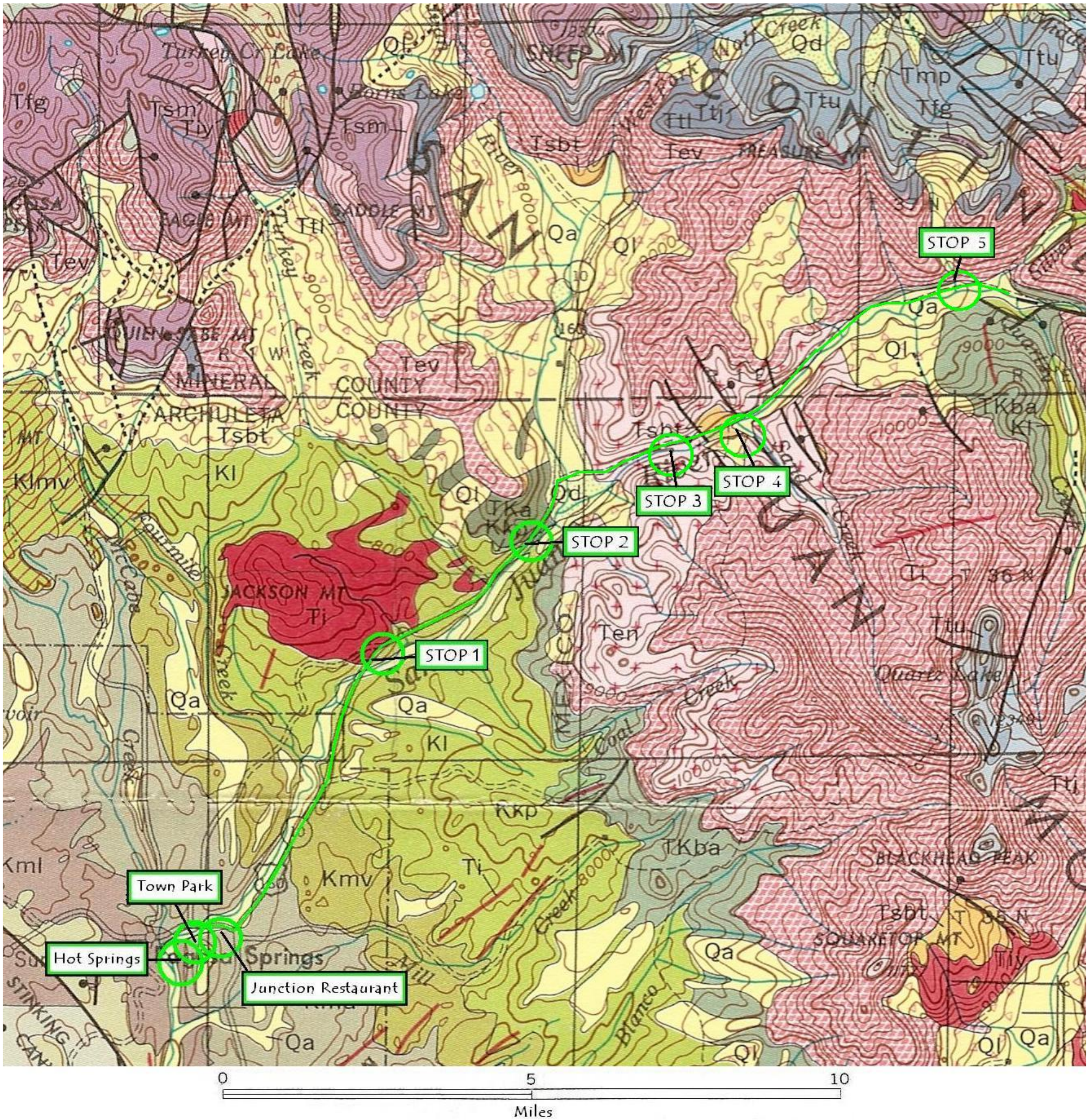
14.2 **Qa**	**<u>STOP 4 - PARK ON THE RIGHT</u>** This is a terminal moraine, the dividing line between the glaciated valley ahead of you and the stream-cut canyon behind. The valley ahead was cut by the most extreme advance of the glacier, but it was not always under ice - when the glacier periodically retreated, floods of meltwater reworked the moraines and other debris left behind on the valley floor. Compare the ground and the stream bed - notice the large amount of clean-washed gravel in the stream, versus the high proportion of sand, silt, and rock flour - fine material ground up by the glacier - still remaining in the moraine. This moraine material makes a deep, well-drained and fertile soil. **<u>ONLY VEHICLES WITH GOOD GROUND CLEARANCE SHOULD PROCEED FROM HERE</u>** - there are rough stretches of road and some streams to ford.
15.7 **Ql**	The road enters private land here (the East Fork Ranch). **<u>PLEASE STAY ON THE ROAD RIGHT-OF-WAY.</u>** This is the true glaciated valley. From here, all the way to the mountains ahead, the valley once lay under 2,000 feet of solid ice. The floor of the valley is broad and flat, and is bounded by steep walls typical of glaciated valleys. Other features are the result of the retreat of the glacier - abundant landslides and slumps (Quaternary age **Ql**), when the support of the ice was removed from the steep walls, and hanging valleys, which open out into space halfway up the walls - the streams which cut these valleys once flowed onto the top of the glacier. Today, these hanging valleys form numerous small waterfalls. A beautiful example of these hanging valley waterfalls is Silver Falls, at the end of the trip. Along the East Fork Road, notice the Clamshell to the right - the high, gray cliff forming the skyline. It is a layer of lava flows from an ancient eruption, exposed by a landslide and now being stripped away by erosion. The river flows in a pattern called a braided stream, the result of highly variable seasonal flow and an abundant supply of sediment - more material than the stream can carry except during extreme floods. The rest of the time, the low-flowing waters thread through channels among gravel banks in multiple streams.
	Recently, specialists in hydrology, the science of river flow, have been working to convert portions of the East Fork and San Juan Rivers from braided to meandering streams, to improve fish habitat and reduce the risk of catastrophic floods. A meandering stream is more efficient at containing the flow within its banks, transporting sediment, and produces better spawning and feeding habitat for trout and other fish species.
18.1	**<u>STOP 5 - TURN LEFT AND PARK AT SILVER FALLS GUARD STATION</u>** This was once used as a ranger station for the Forest Service, and is now rented out to visitors (check with the Pagosa District Office for information: 970-264-2268). Please respect the privacy of those using the station. A short hike leads to Silver Falls. From here, the East Fork Road continues up and over Elwood Pass, the original settlers' route into the San Juan country before Wolf Creek Pass was "tamed". The road is extremely challenging and is not maintained, but many adventurers enjoy the trip. A few miners still hack at the rock in those high elevations, and rarely, panners find a few "colors" or a small nugget of gold in the cold waters of the East Fork. As you return to Pagosa Springs or continue on over the pass, look at the mountains and remember their long history, and imagine the glaciers still to come some distant day. Geology is about the future, as well as the past!

East Fork Fire, Ice and Landslide: *Simplified Geologic Map*



East Fork Fire, Ice and Landslide: *Geologic Map*

From Steven and others, 1974

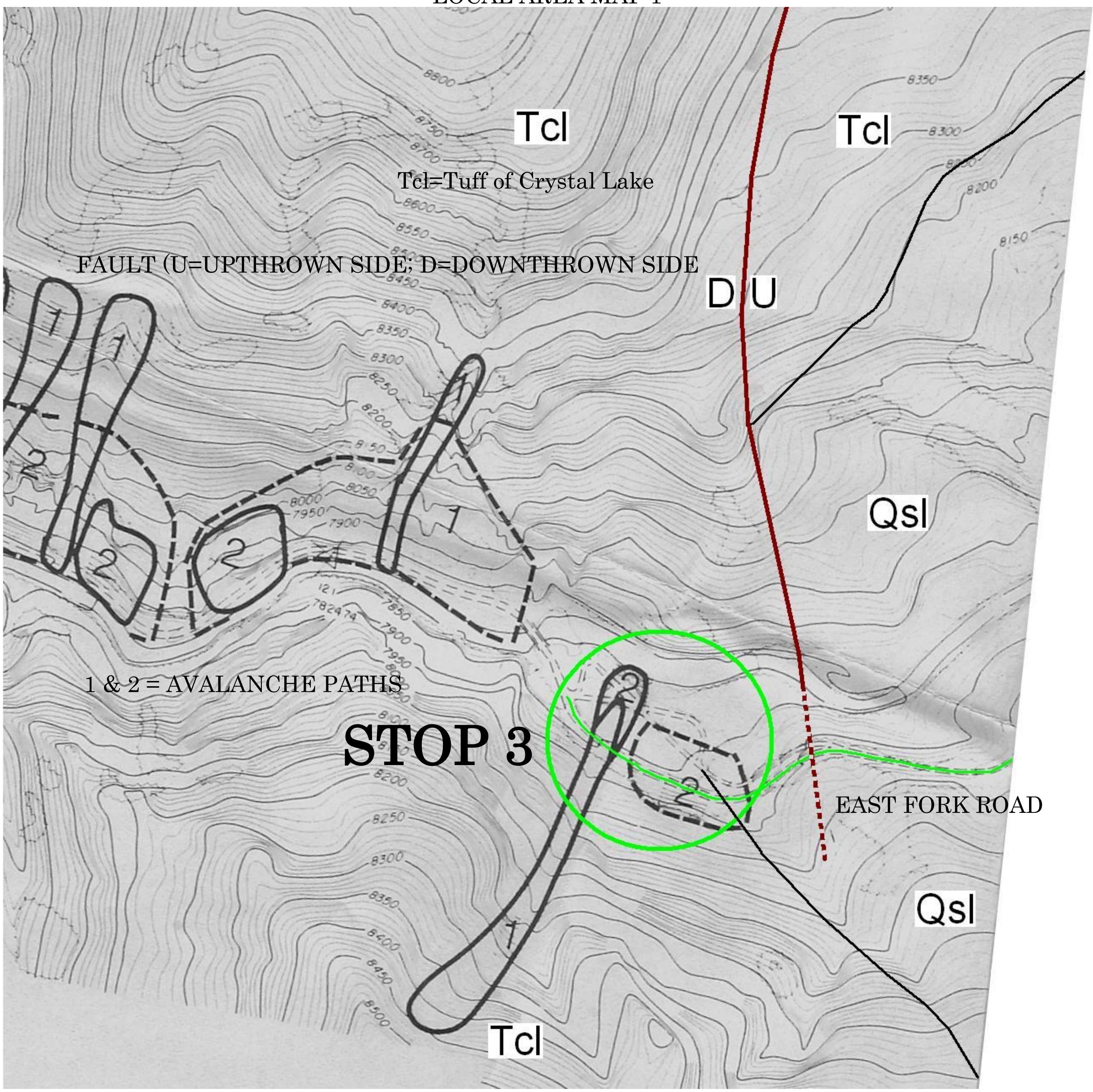


Contour interval 200 feet. See geologic map key at end of document.

EAST FORK LANDSLIDE

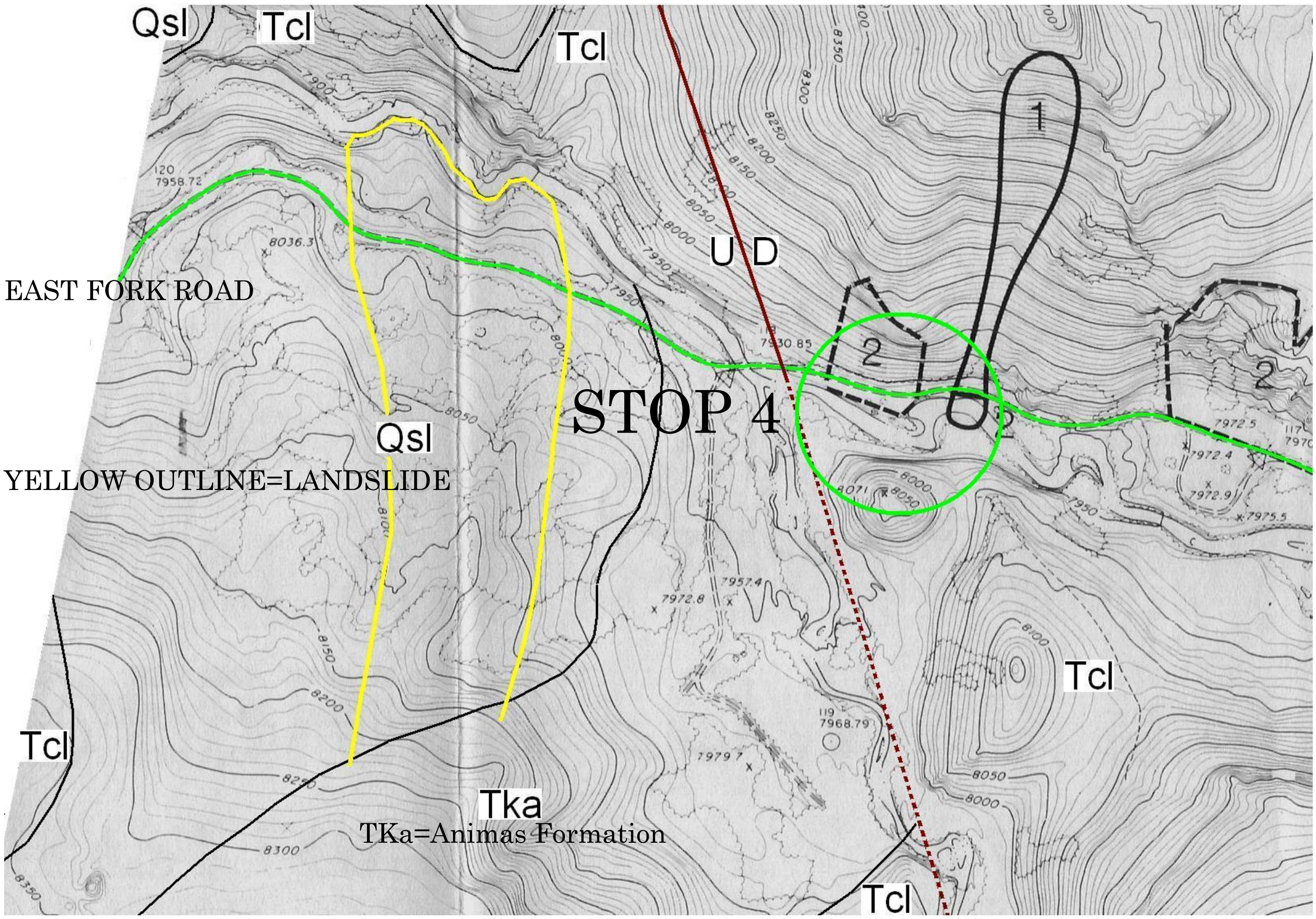
The rocks which are involved in the East Fork Landslide were deposited between roughly 65 million years ago (the Animas Formation and Blanco Basin Formation) and about 27.5 million years ago (eruption of the Silverton Caldera and deposition of the Tuff of Crystal Lake and associated slightly younger volcaniclastic (reworked) volcanic rocks). The local area maps below show the locations of Stop 3 and Stop 4 which bracket the landslide at each end. The slide is within the area of Map 2 below.

LOCAL AREA MAP 1



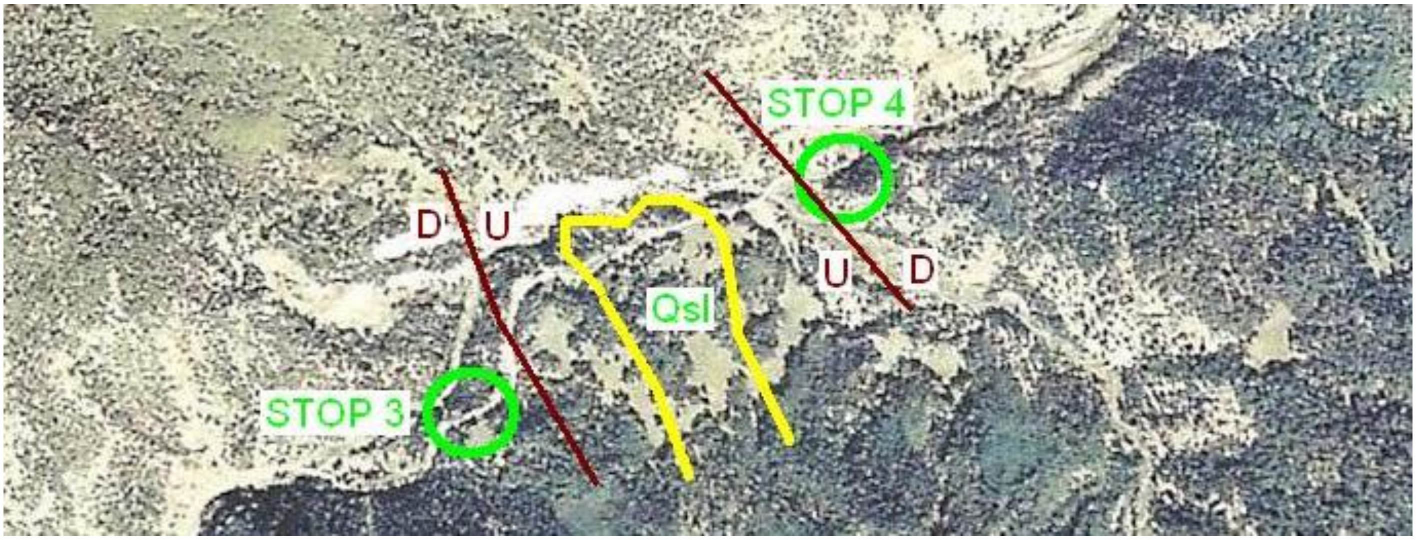
From Stop 3 along East Fork Road: climbing the hill, along the left bank of the river are steep cliff of layerd yellow, red and gray volcanic tuff (the Tuff of Crystal Lake[Tcl]), overlain by thin but harder layers of gray volcaniclastic rock (older volcanic deposits later reworked and redeposited by streams and lakes between volcanic eruptions).

LOCAL AREA MAP 2

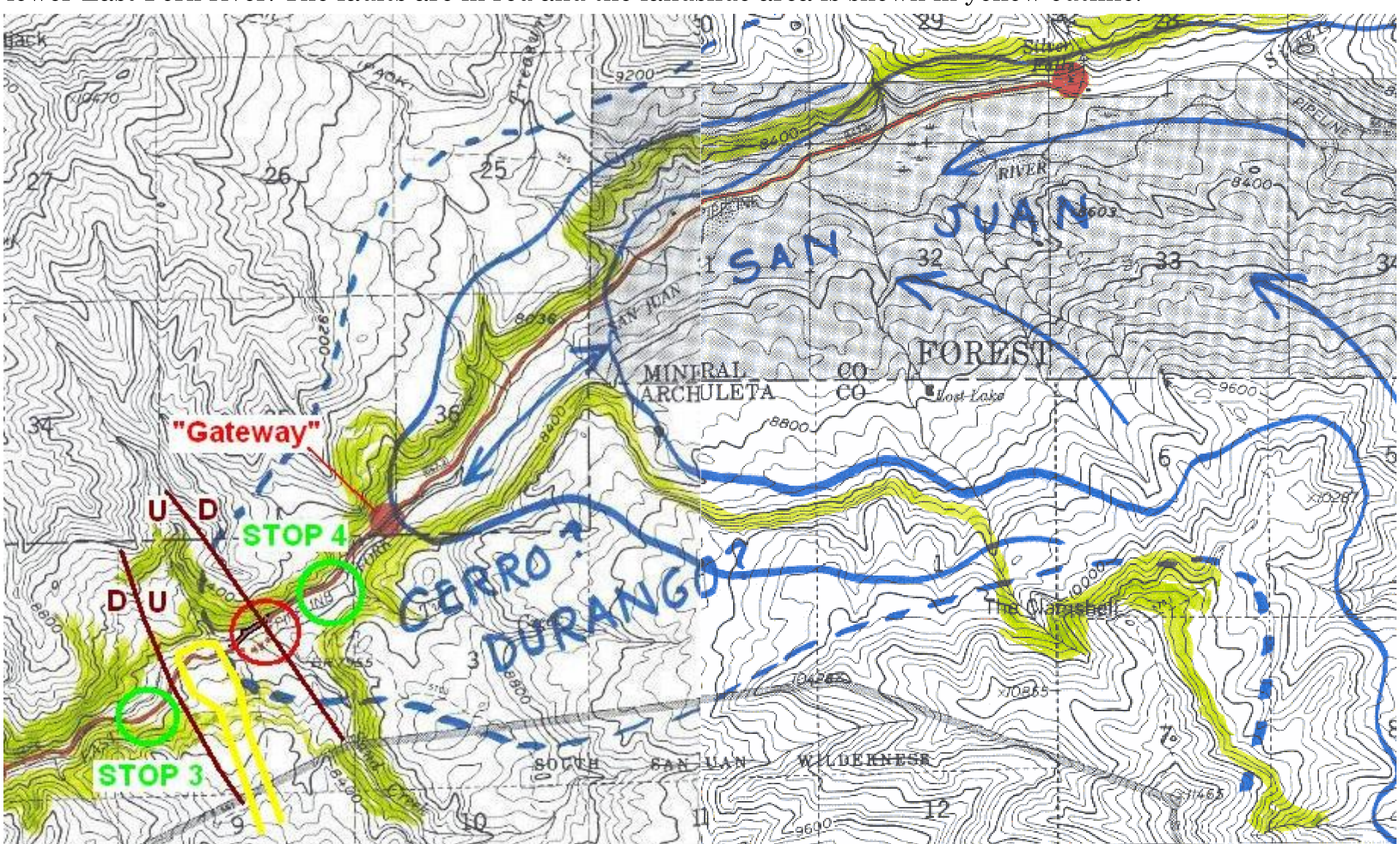


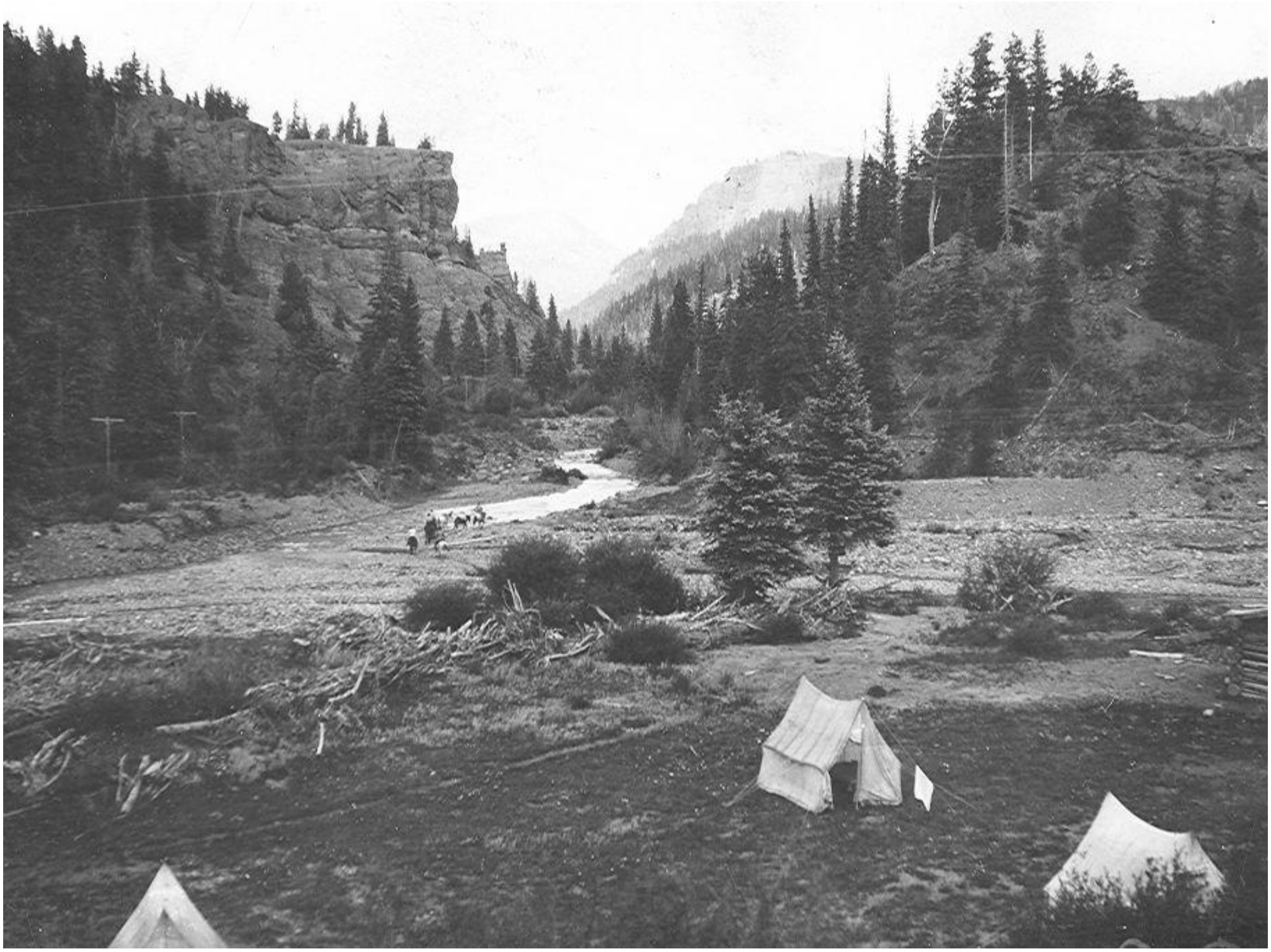
Moving from Stop 3 along the road: the area marked Qsl is a complex of many landslides accumulated over the last 10,000 years. The chaotic shapes of the topographic lines indicate a great deal of movement and change in the local slope. The presence of many small ponds and wet areas indicates that the normal drainage of water has been disrupted often. The current landslide has added its own changes to the local terrain.

This aerial photograph from 2003 shows the confluence of Sand Creek and the East Fork San Juan River at the center of the image. Notice the many open spaces (meadows and wetlands) in the area just to the left of the north-flowing Sand Creek drainage. These are within the area marked Qsl again showing the unstable nature of these slopes. The faults on either side of the slide area are shown in red and the slide outline is in yellow. Stops 3 and 4 refer to the Road Log and Local Area Maps above.



The modern East Fork valley, like almost all the landforms in this part of Colorado, resulted from the intense erosion and scouring of glaciers and their meltwater floods as they melted, between about 18,000 and 12,000 years ago. The map below shows the probable extent of the last 3 major ice advances, from the oldest: Cerro, extending to about the Sand Creek drainage (open red circle); Durango, extending to about the "Gateway" (solid red circle; see following photograph); and the San Juan, which carved the final East Fork Valley. The massive floods of each of these glaciers' melting, in turn, scoured the floor of the valley and cut the narrow V-shaped canyon of today's lower East Fork river. The faults are in red and the landslide area is shown in yellow outline.





Camp at the East Fork in the 1930's – Sand Creek confluence (just before Stop 4 on the Geologic Road Log map and the large red circle on the topographic map above). The stone "Gateway" in the background was cut by flood water from the Durango and San Juan glaciers; the flat top of the "Gateway" was probably the floor of the glacial valley carved out by the earlier Cerro glacier. Beyond the "Gateway" is the terminal moraine of the Durango glacier. The gravel "bars" at the entrance to the private East Fork Ranch (the wide flat valley) are terminal moraines from the San Juan glacier, the last advance of the ice (so far). The location of the camera point is just east of the edge of the landslide.

May 2008: The East Fork landslide moves at roughly 4 feet per day for several weeks, rupturing an 8-inch high-pressure natural gas pipeline and carrying the East Fork Road downhill to the East Fork San Juan River. Early fears that the landslide's rock, soil and trees would dam the river, causing an eventual flood downstream, were eased when the slide slowed and the river managed to maintain its flow. Since summer of 2008 the slide has not moved significantly.

Aerial view of the slide in May 2008. The East Fork San Juan River flows along the left edge of the picture from top to bottom. Sand Creek flows down from the top center to join the East Fork. The bottom of the slide is against the East Fork in the lower left, and extends diagonally up to the right center for about 3,500 feet. Heavy equipment (yellow vehicles at lower left) has reestablished a crude road surface as the slide continues to move, in order to repair and protect the natural gas pipeline that runs along the right side of the road bed. By summer 2009, the slide seems to have stabilized and is no longer moving.

For a short time there was concern that the landslide would dam the East Fork and possibly cause a catastrophic flood that might reach Pagosa Springs. Despite the large numbers of mature conifer trees and the amount of soil and rock impinging on the river, it has not been blocked. The soft volcanic rock along the north bank of the river (the colored layered slope in the picture) may be allowing the channel to erode on that side as more material is dumped into it from the south bank.

If the slide maintains its current (2009) stability, the road may be reopened to some or all vehicle traffic.

A Shattered Landscape: *Geologic Road Log*

Compiled by Glenn Raby, Pagosa Ranger District/Field Office (retired) & Ben Bailey, Pagosa Springs, Colorado

The geology of the southern part of Archuleta County is a study in the processes that formed the Earth and shaped today's landscape. This paper is designed as a self-guiding road trip from the Pagosa Springs Chamber of Commerce Visitor Center, on Hot Springs Boulevard, along Trujillo Road south to the Pinon Hills Ranch gate at Riverview Drive. **PLEASE NOTE: Pinon Hills Ranch is a private gated community; you must have permission from a property owner to enter.**

After a discussion of the geologic history of the area, there is a **ROAD TRIP LOG** which guides your visit. The drive from the Town Park to the end of the road trip is measured in the total mileage driven from the Park. Important driving instructions are printed in **BOLD LETTERS**. You should read over the road trip log before starting out to be familiar with the route and directions. The attached map shows the roads and features noted in the Log. Standard passenger vehicles can easily make this trip, but Trujillo Road is mostly gravel-surface and there are some rough stretches of roadway. Be aware of dust, loose gravel and other vehicles using the road. **The stretch past the town landfill has been known to cause flat tires. Check your spare tire and/or road assistance contacts if you are concerned.**

The accompanying map shows the local features and the major geological formations along the trip route. The map symbols, such as **Kmv**, refer to the geological formations described in the road trip log. A large-scale geological map of this part of Southwest Colorado is available from the United States Geological Survey in Denver or on the internet (Steven, T.A., Lipman, P.W., Hail, W.J., Jr., Barker, Fred, and Luedke, R.G., 1974, Geologic map of the Durango quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-764, scale 1:250,000). The chapter **Pagosa Country Geologic History: the Table** includes a detailed outline through time of Pagosa's geology and list of references.

Pagosa Springs sits in the valley of the San Juan River, on a landscape of Cretaceous-age sedimentary rock -- the ocean-bottom mud of the Mancos Shale. During the last years of the Dinosaur Age, some 80 to 100 million years ago, the shallow sea which covered western North America drained away. A series of river deltas, floodplains, and swamps covered this area. The age of the dinosaurs ended 65 million years ago, apparently in a geologically short moment of climate change and cataclysm. No one knows for sure what ended the 200 million year reign of these great beasts, but their disappearance opened the world for the mammals. As the modern Rocky Mountains rose to the north, this flat, wet landscape with its entombed dinosaur bones was buried by debris washed down from those new mountains; at the same time, immense volcanic forces began to rip and shatter the land.

The San Juan River begins high in the volcanic mountains of the Continental Divide. These mountains, today topping 13,000 feet, are mere remnants of a mighty range of volcanos that formed between 40 million and 10 million years ago. The volcanic peaks, which may have been as high as 20,000 feet, were destroyed by repeated violent explosions; after the last eruptions, they were swiftly eroded to the level we see today by water and ice. Starting about 400,000 years ago, the Earth entered the most recent of a series of glacial periods we call the Ice Age. This period is known to geologists as the Wisconsin Glaciation, and the last retreat of the ice was sometime between 18,000 and 12,000 years ago. The Ice Age itself may not have actually ended; interstades (warm interglacial periods) are common and we may be in such a period between the retreat and advance of glaciers. How long it may be until the next advance of the ice, no one can predict; but if we can trust our understanding of Earth's past and the processes involved, we know that it will certainly happen sometime in the future.

All of recorded human history has occurred since the last of the great ice sheets melted away; the glaciers predate all the great civilizations of mankind. Prehistoric Indians may have seen the last, shrunken tongues of ice, high among the mountain peaks overlooking the San Juan valley. Archaeological finds along the Continental Divide in 1997 show that people were hunting in those wildernesses when the glacier was in its final retreat, about 10,000 to 12,000 years ago.

A SHATTERED LANDSCAPE - ROAD TRIP LOG

Miles	Points of Interest and Driving Instructions
0.0	Set your trip odometer at 0. Depart from Town Park. At the intersection of Hermosa Sreet and Hot Springs Boulevard, turn south on Hot Springs Boulevard (away from downtown) and drive south to the stop sign.
0.6 **Qa**	TURN RIGHT ON APACHE STREET and cross the San Juan River, which drains the Wolf Creek and East Fork Valleys. Much of the sediment in the river bottom is **glacial till** (debris) from the glaciers in the mountains of the Continental Divide, originally deposited as moraines. **Lateral moraines** run alongside the glacier as it flows, and **terminal moraines** form as dams at the lower end of the glacier. These terminal moraine dams can cause lakes of meltwater to form, and when the dams eventually break, huge floods run down the valley below. This must have happened many times over the thousands of years of life of the glaciers. As the glaciers finally melted, floods reworked the glacial debris into a type of sediment called **alluvium**, meaning water-deposited sediment. The accompanying map shows the geologic formations exposed along the trip route, using standard geologic map colors and symbols (such as **Qa**). These symbols are shown in the mileage column to the left, to help you connect the trip log with the geology on the map and on the ground. The heavy lines on the map outline the area where each rock type is exposed. The symbol **Qa** means **Quaternary** (the geologic age of the sediment) and **alluvium** (the geologic formation or material). This format is followed through the trip log below.
1.1 **Kml**	APACHE STREET BECOMES TRUJILLO ROAD; CONTINUE ON TRUJILLO ROAD. This is the Cretaceous-age lower Mancos Shale (**Kml**), deposited about 90 million years ago. The Mancos Shale is locally mapped as the lower (**Kml**) and upper (**Kmu**) units, but in some areas is not subivided and is mapped as **Km**. It weathers into soft rounded hills and dry, steep slopes, with poor soil development. It is made up of fine clay which makes wet-weather driving such an adventure. The Mancos Shale was laid down in thin layers of fine mud of the Cretaceous-age Western Interior Sea which ran from Canada to Mexico. The dark gray color is from abundant carbon, the remains of plants and animals which died and settled to the ocean floor. The sea was about 300 feet deep and generally very quiet. Mud accumulated at the rate of 1 inch every thousand years, except for rare events when storms or floods on land flushed sand into the sea basin. The Mancos Shale is about 2,000 feet in maximum thickness, representing possibly 20 million years of slow deposition. In its dark layers can be found ammonites (coiled shells up to 3 feet across), fish scales and teeth, oyster and clam shells, and other fossils of vanished marine life. Most are very fragile and will not preserve once exposed -- the shale is too soft.
2.7 **Kdb**	On the left is the old Pagosa landfill and Transfer Station. The road turns sharply and descends the **Put Hill Fault Scarp** (shown on the map as a heavy black line). A scarp is the cliff separating the upthrown side of the fault from the downthrown side. The fault crosses Highway 160 to the north and is known as Put Hill. The road is now running across the 100-million-year-old Dakota Sandstone and Burro Canyon Sandstone. Dakota and Burro Canyon are locally mapped as one formation (**Kdb**), which forms the floor of the wide valley the road now enters. The orange-brown color of the stone and the soil that forms from it is the result of oxidation (rust) of the iron contained in the sandstone. Freshly broken stone is gray or white. The Dakota supplies most of the building and decorative stone used in the Pagosa area.

Kdb	The Dakota was laid down as sand and silt along the shifting shoreline as the Cretaceous Western Interior Sea was opening and spreading across the land. The widening sea gradually drowned the Dakota-age river deltas and swamps and beaches. As the land was submerged, the sediment being deposited changed from sand and silt to ocean-bottom mud of the Mancos Shale. It is this difference in sediment type which allows geologists to read changes in the ancient environment from the rocks formed in them. The transition from sandstone to shale marks the end of the land and beginning of the sea in this area (a time that geologists call a **transgression**), and provides a standard way to divide the rock formations. The Dakota weathers in roughly rectangular fragments because of joints (fractures) in the rock. These joints are the result of mountain-building forces which fractured the brittle sandstone. Erosion has stripped away the softer overlying shales and left a wide, flat valley of pine forests and well-drained soil.
5.6 **Km** **Kdb** **Kmv**	**Cascade Avenue; <u>CONTINUE ON TRUJILLO ROAD</u>** The road weaves along the valley floor and the edge of the valley, among low hills of Mancos Shale sitting atop the valley floor of Dakota Sandstone. The cliffs ahead are capped by the harder sandstone of the Mesa Verde Formation (**Kmv**). The Mesaverde represents a brief shallowing of the ancient sea; about 90 million years ago, the Pagosa Springs area lay near the shoreline, with beaches and sand dunes, river channels and deltas, floodplains and swamps. The rocks deposited by these cycles of dry land, shoreline, and shallow sea include thin coal seams, sandstones, shales and mudstones, and tell the story of a short time when the sea retreated (called a **regression**); but eventually, the waters returned to flood Pagosa once more. Here the sequence is very thin, but further west it thickens and the Mesaverde is subdivided into separate formations, forming the impressive cliffs and tablelands of Mesa Verde National Park.
10.0	On the right is the **Pagosa Springs Landfill.** This is located in a thick layer of river-valley deposits (aluvium) in the uppermost Mancos Shale. The hill behind the landfill is capped by the Mesa Verde Formation.
11.0 **Km**	**<u>STOP 1: TURN RIGHT ONTO BURNS CANYON ROAD – JUST PAST MILE MARKER 10. WATCH FOR RED RANCH BUILDINGS ON THE LEFT</u>** Drive ½ mile and park along the right side of the road. This is private land so please stay on the road shoulder. Burns Canyon is carved into the upper Mancos Shale. The cliffs on the north siad of the canyon are capped by the harder rocks of the Mesa Verde Formation. The road has been travelling “upward” in time from older rocks into younger rocks as it heads south.
Kmv	This view of the cliff illustrates the geological process of **regression**, a retreat of the sea from the land. The lower slopes are sea-bottom mud, but as time goes on (moving higher in the cliff), the sea shallows and begins to fill with coarser sands and gravels washing in from the aproaching shoreline. Thin layers of sandstone appear and become thicker and more dominant, until rnally the nature of the rock changes to mostly shoreline beach sand, river deltas and tidal flats, and eventually to dry-land deposits of the Mesa Verde Formation. This sequence of uplift, transition from ocean to tidal flat to beach to dry land, will quickly reverse as we head further south, as the sea reclaims the area (transgression) and Pagosa sinks again to the ocean floor.

12.0 14.9 Kmv 15.2	<u>**CAREFULY TURN AROUND AND RETURN TO TRUJILLO ROAD; TURN RIGHT (SOUTH) AND CONTINUE**</u> The road continues through the upper Mancos Shale. Notice the increasing sandstone layers in the shale. The ancient sea is shallowing and filling as the land is uplifted. Over the next 2 miles, the road “climbs” into the lower Mesa Verde Formation, deposited as the sea drained away. Now the road is crossing through the thickest part of the Mesa Verde Formation. Note the frothy look of the sandstone. The rock is cemented by calcite, a common rock-forming mineral. Ground water dissolves calcite, leaving channels and hollows in the rock. Ahead on the southern horizon is a white “castle” of natural rock, made of the late-Cretaceous age Pictured Cliffs Sandstone (about 71 million years old). His is the same rock formation that forms the twin Chimney Rock spires west of Pagosa Springs. Below the Pictured Cliffs is the Lewis Shale, a virtual twin to the Mancos Shale, formed when the sea reclaimed its domain between 80 and 71 million years ago. The Pictured Cliffs sands are shoreline beachs and dunes, representing the final (so far) retreat of the sea from North America. From the start of the tour to this area, you have passed through, from older to younger, the Dakota Sandstone, the Mancos Shale and Mesa Verde Formation. You are now entering the Lewis Shale. This series of sedimentary rock layers document the times when this area was shoreline (**Kdb** - Dakota), sea floor (**Km** - Mancos Shale), briefly shoreline and beach (**Kmv** - Mesa Verde), and sea floor again (**Kl** - Lewis Shale). We are now entering the Lewis Shale, where our tour will end. Above the Lewis, in the surrounding mountains, are exposed the shoreline beaches, dunes, peat bogs and coal swamps of the last retreat of the sea (**Kkp** - Pictured Cliffs Sandstone and Fruitland Formation), and finally the eroded debris from the young Rocky Mountains which buried the swamps (**TKa** - Animas Formation), and which also hides the moment when the dinosaurs vanished, 65 million years ago.
15.5	<u>**STOP 2: CROSS THE BRIDGE AND TURN LEFT ONTO RIVERVIEW DRIVE AND PARK ON THE RIGHT. WAIT HERE FOR THE GATE TO OPEN**</u> From here, the trip is on private land; please do not leave the trip route.
15.9	<u>**STOP 3: VIEW OF OLD TRUJILLO**</u> We are driving through the lower Lewis Shale. The slopes across the river illustrate the thin dark layers of millions of years of ocean-bottom stagnant mud, interrupted by occasional layers of sand washed in by huge storms and floods from onshore.
17.0	<u>**CONTINUE ON RIVERVIEW DRIVE TO ROCKCLIFF CIRCLE. TURN RIGHT ON ROCKCLIFF CIRCLE**</u> The road continues through the eroded Lewis Shale hills. Look for the first gravel driveway on the right, across from a green junction box marked **J7114** on the left.
17.1 Kl	<u>**STOP 4: TURN RIGHT ON GRAVEL DRIVE AND PARK IN THE TURNAROUND**</u> The property lies within the middle of the Lewis Shale (**Kl**), deposited as thin clay and mud layers at the rate of about 1 inch every thousand years, on the bottom of the 200- to 300-foot-deep Cretaceous estern Interior Sea. The very high organic content of this ocean-bottom mud is shown by its dark color and abundant fossil material (clam and oyster shells, fish teeth and scales, ammonites). The lower levels of the inland sea were probably calm and stagnant, lacking oxygen, which preserved most of the organic material (dead sea creatures) which fell from the surface and middle levels of the water. The Mancos Shale, the rock layer in which Pagosa Springs is located, was deposited in the same inland sea environment and contains the same type of organic debris.

Kl	The thinly bedded sandstone layers typical of this part of the Lewis Shale exhibit trace fossils (sole and drag marks, burrow fillings), fossil shells, ripple marks, mud clasts and occasional limy cement. These indicate energetic to calm flood regimes, probably the result in each bed's case of a single flood event washing sediment into the sea basin's shallow fringes, violently disturbing the sea floor (ripping up mud and clay fragments, depositing broad ripples and dunes, then gradually losing energy and depositing a top layer of fine sand, silt and mud, along with organic material (roots, shells, etc.) carried by the flood water. Biologic disturbance of the flood sediments followed as burrowing creatures made homes and scavenged for food in this soft clay and silt layer. Long periods of quiet sea-floor mud deposits followed these flood sequences, only to be disrupted by new flooding. The color of these sandstones ranges from pale gray on freshly broken surfaces, to dark reddish back with an iridescent sheen. The color is a result of weathering of the rock: the iron contained in the sediment is exposed to water and oxygen, producing iron oxide minerals (limonite, colored orange-red, and hematite, red to red-black) which essentially stain the rock with rust. The very dark color sheen is the result of the formation of an iron-oxide mineral called goethite, which has an "oil-slick" rainbow appearance in bright light. The "cement" which holds the sandstone together is a mineral called "lime" or calcite, the basic component of common limestone. It forms by crystallizing out of ground water in the tiny spaces between the sand grains (most sand, even when tightly packed, is about 50% open space). This cement causes the loose sand to turn into rock (a process called "lithification"), but even the sandstone usually contains up to 40% open space, through which ground water can slowly percolate. This property makes sandstone an excellent natural filter and reservoir for ground water, as well as oil and natural gas.
Ti	The low hills follow dikes (faults intruded by igneous magma, forming vertical walls). The dikes (red lines marked as **Ti** on the geologic map) probably formed between 10 and 30 million years ago. This volcanic mountain-building caused the bedrock to fracture, generally in northeast-southwest trending faults. These faults control the direction of the dikes and hence the direction of the linear hills of today. Later nonvolcanic faults overlap these earlier dikes in northwest-southeast and east-west trending fractures (marked as heavy black lines with ball bars on the down-dropped side). These faults and the earlier dikes controlled erosion of the soft shale during the glacial melting and flooding; runoff followed these weak zones to cut today's channels and canyons. The ancestral San Juan River was subject to massive floods from melting glaciers (about 15,000 to 12,000 years ago), and was responsible for the final shaping of this landscape.
	A water well analysis was completed for ground water in the area. A comparison of the chemistry of this water hosted by the Lewis Shale and the chemistry of the water of the Pagosa Hot Springs, emerging through the surface exposure of the Mancos Shale, shows some intersing similarities and differences. This comparison is not scientific, simply a general comparison.

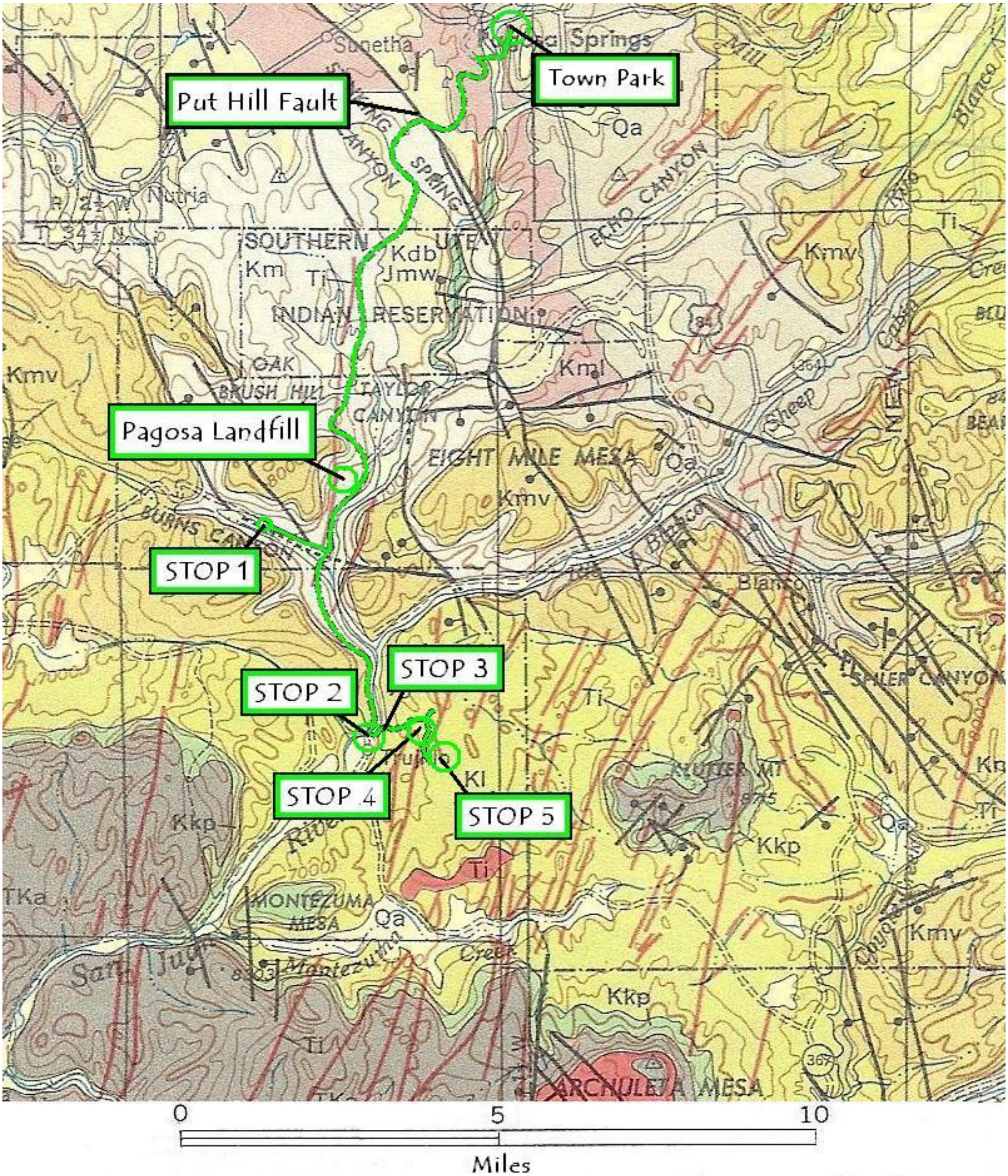
Mineral/Element (Mg/L)	**Pinon Hills Lewis Shale**	**Pagosa Hot Springs Mancos Shale**
Sodium	1228	790
Chloride	106	180
Iron	0.05	0.08
Manganese	-0-	0.23
Sulfate	-0-	1400
-----------------------------------	-----------------------------------	-----------------------------------
pH	7.31	App. 7

	The ph (measure of the acidity of the water) falls in the range of normal drinking water (6-8). The Lewis Shale water is higher in salt content (sodium) than the Hot Springs, having a distinctly "salty" taste. Iron content is similar. The Hot Springs has a measurable amount of manganese (and other metals not analyzed for in the Lewis Shale water). The most important difference is the sulfate content. The Lewis Shale water has no measurable sulfate, while the Hot Springs water has enough to give it a powerful "sulfur" smell. Because the chemistries of the Lewis and Mancos Shales are very similar, the differences in the water samples are due to the deeper source of the Hot Springs water. The higher content in the Hot Springs of metals, chloride and sulfate comes from the deep, hot ground water leaching chemicals from the geologic formations beneath the shale layers, and the different chemistry of that deep water itself. Once it makes its way up into the shales, it is mixed and diluted with shallow ground and surface water, which has the same basic chemical content as the Lewis Shale well water. Normally these very different water regimes are kept separate by the intervening geologic formations; because the Hot Springs is fed hrough a complex series of faults and deep channels, the two types of water are allowed to mix.
	The view from the property is dominated to the south by Montezuma Mesa, a "tableland" capped by relatively hard Pictured Cliffs Sandstone, and a similar unnamed mesa to its east, capped by a thin "laccolith" (lake-shaped body) of igneous rock, the same magma that formed the dikes, only intruded horizontally between rock layers instead of as vertical dike walls. Archuleta Mesa is the same type of formation, only much larger, and may have been connected to the small mesa before glacial floods cut Montezuma Creek between the two. Klutter Mountain on the eastern horizon may also have been part of the same igneous complex. These very hard igneous rocks form a protective "caprock" that keeps the mesas from eroding away as quickly as the shale hills. American Indians probably began to migrate into this area after about 12,000 years ago, when mountain passes became clear of glacial ice and snow. The land was wetter and more lush then, and the Indians likely camped and later built permanent homes here, to make use of the soil for crops and to hunt the abundant game animals. Artifacts and a probable Pueblo II age structure indicate residential use about 900 years ago. More recent items show that settlers and homesteaders replaced the Indians starting in the middle 1800's, especially when the Hot Springs were being considered for a military sanitarium for Civil War veterans.
17.4	**RETURN TO ROCKCLIFF CIRCLE; TURN RIGHT AND CONTINUE** The road continues through the eroded Lewis Shale hills. Look for a gravel driveway on the left, just past a green junction box marked **J7119** on the right.
18.2 **Ti**	**STOP 5 - TURN LEFT AND PARK AT THE END OF THE DRIVE.** The low hill ahead has a "spine" of volcanic rock, a vertical intrusion called a dike. Volcanic activity began with the opening of the Rio Grande Rift in central and northern New Mexico. This mountain-building period created a series of more or less parallel fractures or faults in the brittle bedrock, with vertical movement along faults of several hundred feet. Because of rising bodies of magma (molten rock), more and more volcanoes were erupting across this region, building the massive San Juan Volcanic Field. The steadily increasing volcanic mountain-building eventually buried the Animas Formation in thick layers of eruptive debris ("pyroclastic" rock) and volcanic sediments ("volcaniclastic" rock: pyroclastic material later reworked by sedimentary processes of erosion and weathering). These rock layers make up the Blanco Basin Formation.

	At about 28 million years ago, the pressure of the rising magma caused a massive volcanic eruption, the largest known on Earth so far, called the La Garita Caldera eruption. This blast threw over 1,500 cubic miles of rock and dust and lava into the air, excavating a hole 70 miles across from north to south and 45 miles wide from east to west. The southern margin of this huge crater, larger than Mineral County, is today's Continental Divide, the San Juan Mountains at Wolf Creek Pass. The entire Four Corners area was buried in thick layers, possibly a mile deep, of volcanic debris after this eruption. From that day, over the next 10 million years, smaller volcanoes continued to erupt, burying the crater with later volcanic rock, and today there is little visible evidence of this monstrous eruption. Between about 20 and 10 million years ago, molten rock squeezed up into the more or less vertical faults and fractures, cooling and crystallizing into "dikes" of igneous rock. Both the magma and the shales it intruded were affected: the magma absorbed water from the cooler wet shales and chilled quickly, forming small crystals because of the rapid cooling; the shale that was in contact with the molten rock was baked by the heat (about 1,500 degrees F.) of the intruding magma into a hard near-ceramic rock called hornfels. In the Pagosa-Trujillo area and south into New Mexico, a "swarm" of parallel igneous dikes formed, trending north-northeast, filling fractures created by stress from the northeast and southwest dating from the Laramide mountain-building period, 80 to 35 million years ago. These dikes are oriented vertically and are generally 2 to 6 feet thick where exposed and are discontinuous, running for tens to hundreds of feet before pinching out; at the end of one dike, a new dike offset by several feet typically begins. In some places two or three dikes run parallel for short distances. They are "mafic" (ferro-magnesian) in composition, dark gray in color and weathering to dark rust-red and brown. These dikes were probably "feeders" for localized fissure eruptions that spread thin lava sheets across the paleotopography. From about 10 million years to about 1 million years ago, the heat beneath the Colorado Plateau has been fading, ending the cycle of volcanic eruptions. Volcanic eruptions gradually subsided and generally ceased about 10 million years ago. The Pagosa and other hot springs are the last remnants of this volcanic energy. Weathering and erosion has torn down much of the volcanic mountains and filled valleys and basins with sediment. Starting about 1 million years ago, the last Ice Age began. Glaciers advanced and retreated, wearing away the higher peaks and dumping huge layers of broken rock, sand and silt into the valleys scoured out by the rivers of ice. Flooding as the ice melted finished wearing away the last of the great volcanoes to the north. The swollen rivers of melt water swept across the property, cutting down into the relatively soft volcanic deposits and sedimentary layers beneath (the Blanco Basin, Animas, Fruitland, Pictured Cliffs, and upper Lewis Shale – something like 76 million years of Earth history, ground away and carried off by ice and water). Nothing remains of these rock layers on the property today; the surface is made up of shale hills held up by their "backbones" of igneous dikes. Both the crystallized igneous rock of the dikes and the hornfels (baked shale) flanking the dikes are harder than the surrounding shale, so these rocks resisted erosion more effectively than the shale between the dikes. Most of today's ravines and smaller drainages lie between the dikes for this reason, since water erodes the softest rock available. The surface seen today probably was substantially formed by about 10,000 years ago, and has not been much modified by erosion since. There is little erosion by running water today aside from infrequent ravine flooding.
	RETURN TO ROCKCLIFF CIRCLE; TURN RIGHT AND DRIVE TO RIVERVIEW DRIVE; TURN LEFT AND DRIVE TO THE GATE. STAY RIGHT AND DRIVE SLOWLY TO ALLOW THE GATE TO OPEN AUTOMATICALLY. TURN RIGHT ON TRUJILLO ROAD AND RETURN TO PAGOSA SPRINGS

A Shattered Landscape: *Geologic Map*

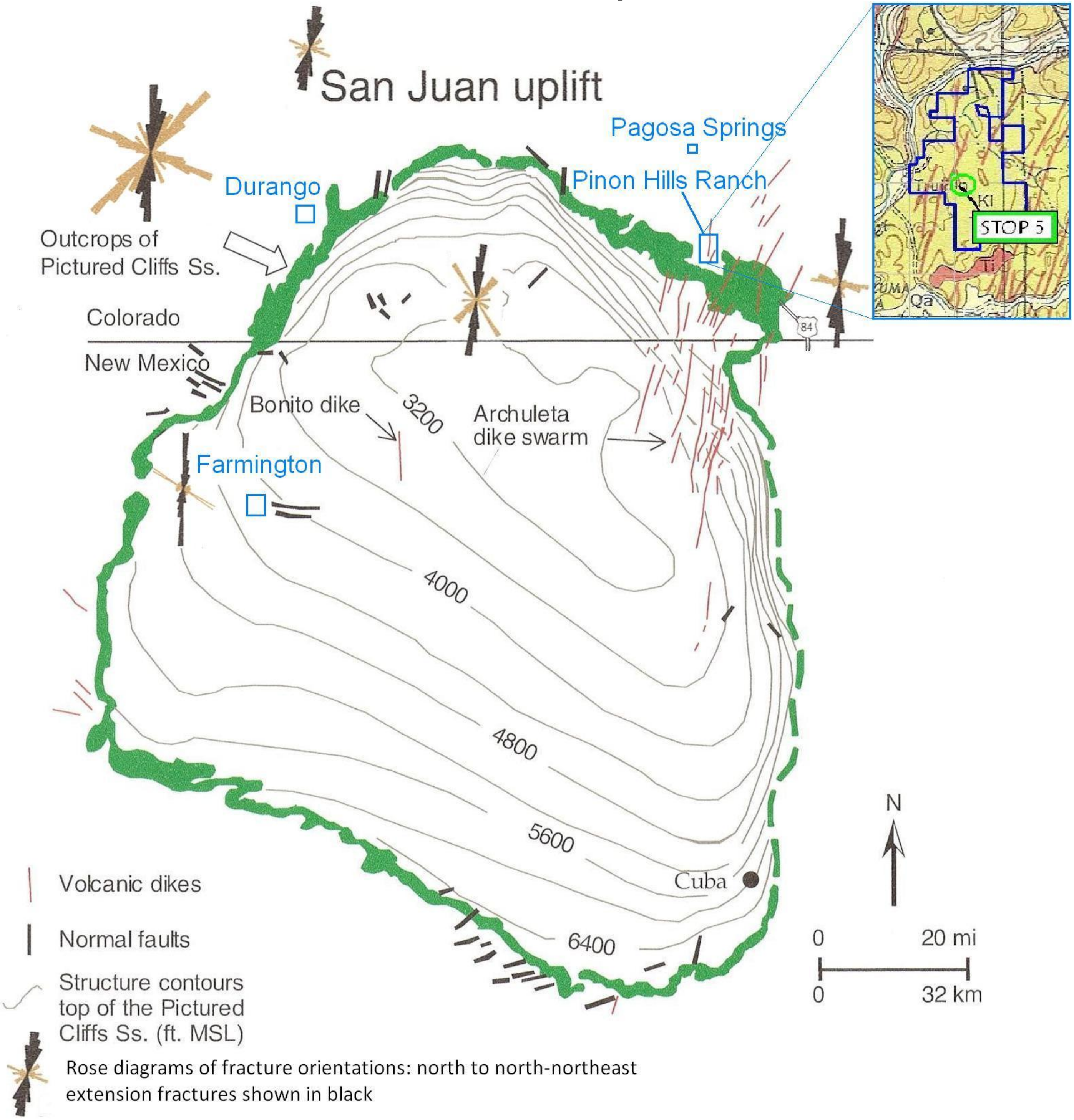
From Steven and Others, 1974



Contour interval 200 feet. See geologic map key at end of document.

A Shattered Landscape: *Archuleta Dike Swarm*

Modified from Lorenz and Cooper, 2003



The Archuleta Dike Swarm consists of hundreds of parallel dikes: thin vertical sheets of igneous rock, crystallized from magma which intruded into extension fractures. These fractures were caused by compressional stress from the San Juan Uplift, which pushed southwest against the northern San Juan Basin (outlined in green along the Pictured Cliffs Sandstone outcrop). In the Pinon Hills Ranch area (dark blue outline in inset box), these dikes form the "spines" of low hills in the soft Lewis Shale. Dike "swarms" are made up of numerous parallel dikes which were intruded more or less at one geologic event (over hundreds to thousands of years) and typically were the feeders for local fissure eruptions that covered the landscape with sheets of lava. The Archuleta dikes are made up of iron and magnesium minerals ("mafic") and weather to red-brown secondary minerals and soil. They are often bounded by a thin "rind" of hornfels (heat-hardened shale). For explanation of the geologic symbols in the inset map, see the key at the end of this document.

A Shattered Landscape: *Dike Outcrop at Stop 5*

At Stop 5 on the field trip, walk from the parking area towards the hill rising against the skyline. Notice the sharp wall of rock that tops the hill- this is actually three dikes, named here the **hilltop dike**, the **skyline dike**, and the **dike "dam".** The hilltop and skyline are parallel dikes, but they likely merge further to the north (top of the photo). The house at the top of the hill sits directly atop one of the dikes. The dike "dam" is a separate dike, but it closely lines up with the skyline dike. Each of these dikes intruded into a separate fracture or fault, but they occupy a zone of parallel fractures rather than one single fault line. Usually one dike intruded into one fracture for several yards to hundreds of feet, but as you follow it, it will pinch out and within a short distance a new dike will appear, offset only a yard or so to one side or the other. The **cross-road dike** is a continuation of the dike "dam", but it is hard to see until you cross Rockcliff Circle road to the south. For some distance there are actually three thin parallel dikes, holding up the small hill with the tree shading its crest.

These dikes were intruded within a geologically short time span, hundreds to thousands of years, but it is likely that each dike segment was intruded in one "spurt", releasing the heat and pressure of the magma below until it built again, and since that fracture was already filled, the next "spurt" found it easier to intrude a parallel fracture. This creates a "swarm" of parallel dikes, physically close to each other but each a separate vertical sheet of rock, all following one broad continuous alignment. The many parallel fractures are the result of intense pressure from the northeast, forcing the rock to shatter and spread (extend) perpendicular to the stress. These are called extensional fractures. They did not form open fissures, waiting for magma to some day fill them up; they remained tightly sealed until pressure from below, rising with the growth of the huge San Juan Volcanic Field, caused upward flexing and allowed magma to force its way to the surface through the cracks. The dikes fed long fissure eruptions that created sheets of lava, covering the land for miles around, until they cooled into rock.

South Fork to Creede: *Geologic Road Log*

Glenn Raby, Pagosa Ranger District/Field Office, Pagosa Springs, Colorado (retired) & Larry Larason, Gallup, New Mexico

This drive takes you along Colorado Highway 149 across a very disrupted landscape. The San Juan Dome rose during the Laramide Orogeny at the end of the Cretaceous and was eroded down to the Precambrian basement rocks in some places before volcanic eruptions buried it beneath lava flows and blankets of ash. Then explosive eruptions occurred from around 28 to 22 million years ago. Ash falls in the badlands of South Dakota, about 1200 miles downwind, are believed to have come from these eruptions in the San Juan Mountains. The eruptions were probably part of what has been called an "ignimbrite flareup" that happened across one million square kilometers of Mexico and the western United States beginning about 35 million years ago. The ignimbrite was largely composed of rhyolite, an extrusive form of granite. Because it is highly siliceous such magma is quite viscous; it tends to explode rather than flow like basalt. Basaltic magmas come from the mantle, granitic magmas from the crust. What caused such an extensive portion of the earth's crust to melt and explode is uncertain, but it probably relates to the shallow subduction of the Farallon Plate that was involved in the Laramide Orogeny. The "ignimbrite flareup" seems to have been concurrent with the opening of the Rio Grande Rift, although the relationship between the two events is poorly understood. Later eruptions in the Jemez area of New Mexico may be the last events of the "ignimbrite flareup."

The explosive eruptions created a complex landscape, and faulting further complicated the picture. After the magma chambers were emptied by the explosive eruptions, the overlying rock sank into what is called a caldera. At least seven, partly overlapping, calderas are clustered in this region. In most of the calderas additional molten rock rising into the emptied magma chamber pushed up on the fallen rock to create a resurgent dome. Sometimes the rising magma broke the surface creating subsequent eruptions. About a million years after the eruptions ceased, hydrothermal mineralization began, but in this cluster it was largely confined to the Creede Caldera, although to the west it also occurred in other calderas, such as the Silverton. As the mineral laden waters rose along faults, they left behind compounds of silver, gold, lead, iron, zinc and barium.

The largest of the San Juan eruptions was the La Garita ["lookout" in Spanish], which exploded 27.8 million years ago. During a period of 3-7 days 5000 cubic kilometers [more than 3000 cubic miles] of Fish Canyon Tuff was expelled. The caldera is 35 x 75 kilometers [22 x 47 miles] wide. This is believed to be the largest eruption that ever occurred on the planet. A close second is the Toba Caldera on Sumatra, Indonesia that blew up about 75,000 years ago expelling 2800 cubic kilometers of tuff. Although the Toba eruption was somewhat smaller than the La Garita, Toba is blamed for the near extinction of the human race; it is believed that only a few thousand people survived the worldwide cool down and acid rain to continue the species, and this accounts for the minimal genetic diversity found in humans. Another rival for the largest eruption is the caldera created 600,000 years ago at Yellowstone, which is 45 x 75 kilometers wide. Nearly buried by subsequent eruptions, it took almost 30 years to map the full extent of the La Garita Caldera. Peter Lipman, who identified it, sees it as larger than some other geologists. His plot of the La Garita Caldera subsumes all the other seven eruptions in this cluster that occurred over the next 1.5 million years. The Creede Caldera, probably the youngest of this cluster, is about 10 miles in diameter, smaller than the La Garita, but very impressive on its own.

The accompanying map shows the local features and the major geological formations along the trip route. The map symbols, such as **Kmv**, refer to the geological formations described in the road trip log. A large-scale geological map of this part of Southwest Colorado is available from the United States Geological Survey in Denver or on the internet (Steven, T.A., Lipman, P.W., Hail, W.J., Jr., Barker, Fred, and Luedke, R.G., 1974, Geologic map of the Durango quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-764, scale 1:250,000). The chapter **Pagosa Country Geologic History: the Table** includes a detailed outline through time of Pagosa's geology and list of references.

SOUTH FORK TO CREEDE - ROAD TRIP LOG

In South Fork, Colorado, turn onto Colorado Highway 149 at the intersection with US Highway 160, heading for Creede.

The road follows the North Fork of the Rio Grande River in a graben valley. On the south side of the highway the Fish Canyon Tuff **(Tfg)**, ejected from the La Garita Caldera, forms the upper slopes of the cliffs. On the other side the Masonic Park Tuff **(Tmp)**, erupted from the Mount Hope Caldera, the earliest one in this area, is pushed up on a fault to show at the lower portion of the cliffs.

Milepost 1. Cross the Rio Grande River. This is supposed to be a good gold panning area with agate, aquamarine and tourmaline, as well.

Milepost 3. Masonic Park Tuff filled a low area near the settlement of Masonic Park. This is the type location for this tuff.

Milepost 4. Enter Mineral County and the Rio Grande National Forest. Mineral County is 96 per cent federal land. Both the San Juan and the Rio Grande National Forests occupy most of it, with the Weminuche Wilderness Area taking a large chunk of the two forests. There is no agriculture in Mineral Co. and Creede is the only town. Creede had a population of as much as 10,000 during the boom years; today Mineral County's full time population is only about 850. Spar City, another village in Mineral County during the mining years, is now a private resort.

Fish Canyon Tuff has columnar joints and occupies the upper ¼ of the cliffs on the east. It overlies the Masonic Park Tuff. On the west cliffs from 11:00 to 2:00 include the La Garita Caldera wall.

There are at least two other tuffs here, but it gets too complicated to pick them all out.

Milepost 8. Conglomerate cliff on right. A steel railroad bridge in the canyon on the left marks a branch of the Durango and Rio Grande Railroad that once ran from Alamosa through Del Norte and South Fork to Wagon Wheel Gap. Farming began in Wagon Wheel Gap around 1840, and the D&RG had a station here by 1883. The area was popular with tourists who wanted to fish in the Rio Grande, take hot mineral baths, and visit Wheeler Geologic Area.

Wagon Wheel Gap, a narrow passage through the wall of the Creede Caldera, is ahead. Wagon Wheel Gap is so named because a large wagon wheel was found here that was supposedly left behind by miners led by Charles Baker as they left the Silverton gold fields. Somewhere ahead on private property was a small fluorspar mine.

Milepost 9. The Wagon Wheel Gap lava dome partially filled the Creede Caldera; its lava is visible on the cliffs in the most constricted part of the gap, especially in the upper cliffs on the west.

Milepost 10. Lake bed sediments that formed in La Garita Caldera appear in a road cut ahead. They are angular, immature, and coarse grained. Concrete barriers have been placed to keep the unconsolidated rock from falling on the pavement.

Milepost 11. Lake sediments are nicely layered as the highway follows the moat of the Creede Caldera. After the explosive eruption emptied the magma chamber, the overlying rock collapsed into a caldera. Later, as more magma flowed upward into the chamber, it pushed up a resurgent dome named Snowshoe Mountain in the center of the crater. The central caldera formation is the Snowshoe Mountain Tuff (**Ts**). Around the dome water collected inside the rim of the caldera to form a lake. This is called the "moat", because it surrounded the dome in a roughly circular fashion. The Rio Grande River [North Fork] flows into the Creede Caldera on the west, follows the moat in a semi-circle, and exits the caldera through Wagon Wheel Gap.

Milepost 12. Ahead through Wagon Wheel Gap is the resurgent dome of the Creede Caldera, Snowshoe Mountain. It fills much of the caldera and is more than 3,000 feet higher than the caldera wall.

Milepost 14. Railroad bridge crosses the Rio Grande on the left. The railroad line was extended ten miles from Wagon Wheel Gap to Creede in 1891 by David Moffat, who had purchased the Holy Moses Mine from Nicholas Creede. Moffat took free shipping on the trains until he had recovered his construction costs and then gave the tracks to the D&RG. Spur lines once extended short distances up the two forks of Willow Creek to better serve the mines. The D&RG discontinued passenger service to Creede in 1932. By 1973 trains no longer hauled the ore from the mines. The highway crosses the narrow gauge tracks several times ahead. An investor purchased this track hoping to create another tourist line similar to the one between Durango and Silverton. Some people living in Creede have resisted his efforts, however, in 2003 it is expected that a train will be running between South Fork and Creede twice daily during the summer months.

Milepost 14. National Forest Service viewpoint pullout is ahead. Here you can get a better view of the moat deposits. The Creede Formation **(Tcd)** consists of shale laid down in the shallow waters of the moat, as well as travertine deposited by hot springs. The shale is well known for fossils of leaves, insects, and feathers, as well as casts of evaporite crystals, indicating periods of aridity or playa situations. Even after erosion the Creede Formation is 2400 feet thick in places, giving a good idea of the original size of the caldera.

You can see the La Garita Mountains to the north. These mountains are a resurgent dome within the La Garita Caldera and are made up almost entirely of the Fish Canyon Tuff, nearly a mile in thickness.

Pool Table Road goes to near Wheeler Geologic Area. Although John C. Fremont may have been the first White man to see it in 1848, the grotesquely eroded volcanic ash beds were named for Lt. George Wheeler, who led an military survey of the Southwest. The area was once the second most visited tourist attraction in Colorado after Pike's Peak. It became a National Monument in 1908, but because it lacked automobile access and tourists no longer expected to ride horses to scenic places, it was decommissioned in 1933. Access is still difficult, requiring 4-wheel drive, and visitors must hike to see the area.

Milepost 15. At 2:00 is a "fan" of "sagging" layers of ash and columnar jointed ash flows that filled a paleo-valley.

Milepost 18. Junction with Deep Creek Road on left ahead.

Watch for travertine deposits laid down in ancient hot spring, now long dead, their heat exhausted many centuries ago.

Entering Creede. Nicholas Creede discovered a silver lode along Willow Creek in 1890. The town grew in a matter of weeks to an eventual peak population of 10,000. Several notorious characters made their homes here for a time, including Calamity Jane and Bat Masterson, who served as town marshal. Bob Ford, "the dirty little coward, who shot Mister Howard", i.e., the man who killed Jesse James, was shot in turn at his own saloon in Creede by a friend of the James family.

Less well known, but important to Creede's history was Soapy Smith. He arrived in 1892 and began a bunko operation involving five-cent bars of soap. He would stand on a street corner with the soap on a tripod stand. He wrapped the soap with blue paper in which he occasionally placed 10, 20 or 100 dollar bills. His victims could buy a bar for only $5.00. Of course, very few of them ever got their money's worth. After moving from Denver to Creede, he quickly became the "Boss", running the town with a group of henchmen. After the silver crash of 1893 his extortion racket became unprofitable in Creede and he moved on to Skagway, Alaska, where he was shot to death in 1898.

A week after Creede installed electric street lights, newsman Cy Warman penned a poem that commemorated that event and captured the reputation of the mining camp. It included the famous line, "It's day all day in the daytime, and there is no night in Creede."

Mines at Creede produced 80 million tons of silver in four years, but the settlement almost became a ghost town after the silver panic of 1893. It revived for a time as lead and zinc were mined along with silver from the 1930s until mining ceased in 1985. The last Colorado boom town is now best known for the Creede Repertory Theater that began in 1966 and has become a big draw during the summer months.

The mines were north of town in the narrow canyons of the two forks of Willow Creek. The geology here is complicated because younger eruptions created craters that overlap older ones. Willow Creek flows through the Creede Graben that cuts through the wall of the Creede Caldera, but opens into the resurgent dome of the Bachelor Caldera, which erupted about a million years earlier. Mineralized waters flowing upward through faults related to the graben created the metal deposits. The most productive of the veins consisted of amethyst quartz containing silver, lead and zinc. Turquoise has been found in the vicinity, but only as float, carried by streams from an unknown source in the surrounding mountains.

Follow Highway 149 into Creede, turn left at the highway bridge and proceed along 149 south out of Creede. At about mile 25, the highway turns sharply right at an intersection. This is locally known as **Airport Corner**. Park on the right at the foot of the slope. This exposure of the Creede Formation has numerous fossils of plant leaves and twigs, feathers, insects, casts of evaporate crystals, manganese dendrites (fern-like staining on the rock face), and iron concretions. Split the thin layers of shale to find nice examples. These are the moat deposits of the Creede Formation **(Tcd)** that filled the ring-like depression around the resurgent dome of Showshoe Mountain Tuff **(Ts)** following the initial caldera eruption. The area must have been a beautiful sight once the volcano calmed down and life returned, with its central dome surrounded by forests and a wide, blue ring-shaped lake. Volcanoes build new landscapes even as they destroy old ones!

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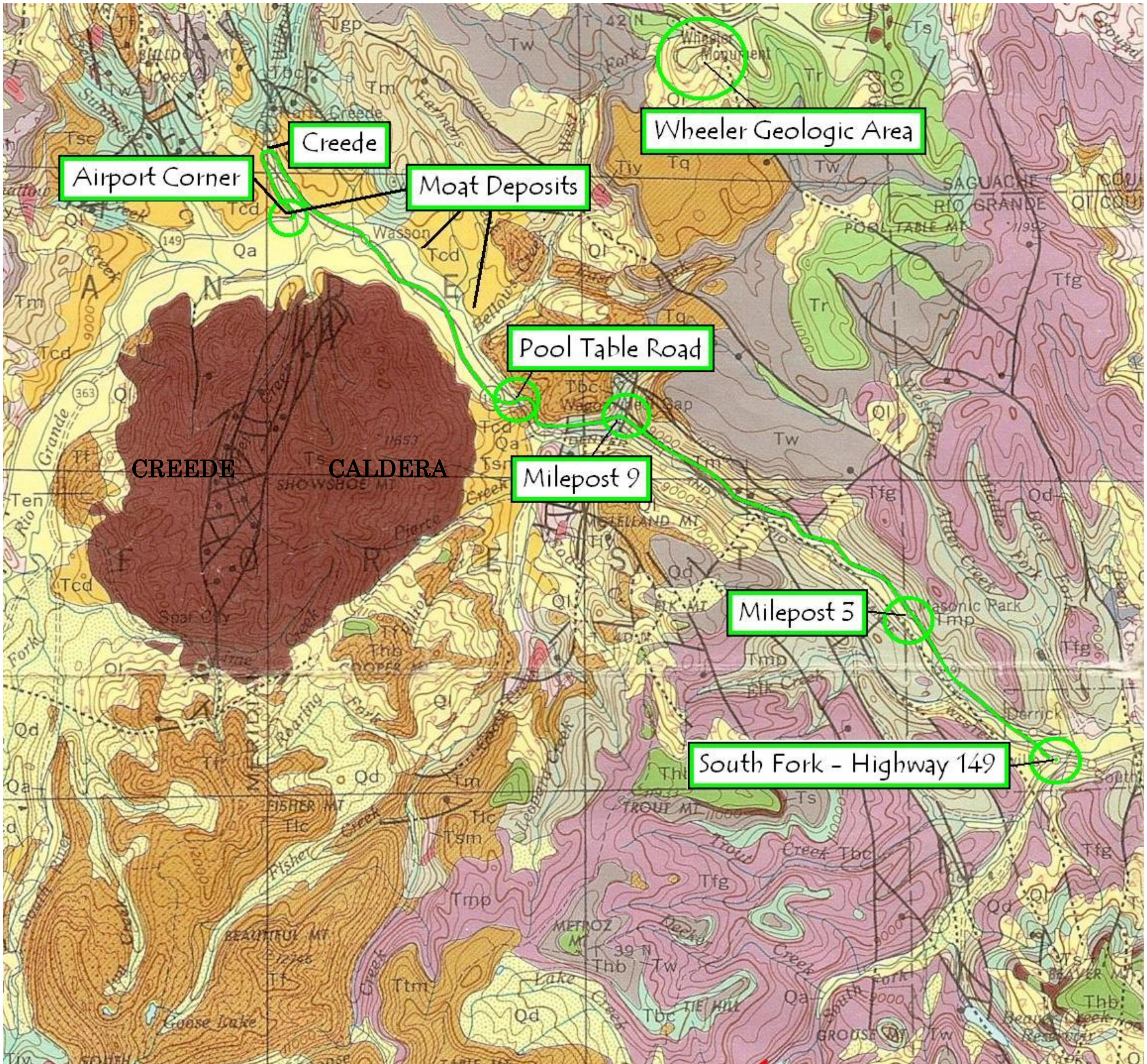
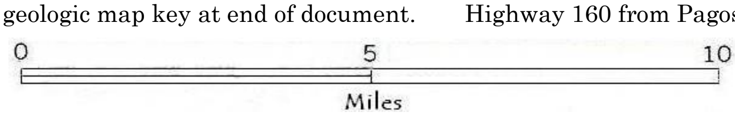
South Fork to Creede: *Geologic Map*

From Steven and Others, 1974



Contour interval 200 feet. See geologic map key at end of document. Highway 160 from Pagosa Springs via Wolf Creek Pass



Ice Cave Ridge: *Geologic Road & Trail Log*

Compiled by Phyllis Wheaton & Glenn Raby (retired), Pagosa Ranger District/Field Office, Pagosa Springs, Colorado

Geology is the study of the Earth's rocks, minerals, structure and processes. The first real geological science was organized in the middle 1800's in England, Scotland, and Europe as an attempt to understand how mineral deposits formed and why the modern landscape looked the way it did. The first geologists faced some difficult questions. Why did some rocks cut cleanly across other rocks? Have volcanoes, earthquakes, and erosion always worked at the same rate, or have they changed with time? How long does it take to build a mountain and to wear it away? Why do we find remains of plants and animals that have turned to stone, and are encased in rock? Why do we find sea-floor creatures fossilized at the tops on mountains and in the deepest deserts where water never flows? How old is the Earth? Many of geology's questions are still unanswered, but geologists have begun to understand the broad outline of the Earth's structure and how it has produced the rocks and minerals we see today. In the Pagosa Springs area, we can see a small part of that complex and beautiful machine that is our world. This field trip will cover only a short piece of geologic time, from the Dakota Sandstone to the sediments being laid down today - a trip of about 100 million years. As long as this seems, it is only about 2 percent of the earth's estimated 4.6 billion-year age. Yet it spans the death of the dinosaurs, the rise of the mammals, the birth of the Rocky Mountains, and the age of Mankind.

This paper is designed as a self-guiding road and trail trip. The road log below lists **total road mileage**. It begins at the intersection of US Highway 160 and Piedra Road (County Road 600), and continues along Piedra Road north to the Piedra River Trailhead. From the trailhead, the foot trail runs for about ¾ mile to the Williams Creek overlook. Driving directions are written in **BOLD LETTERS**. It helps to read ahead before you arrive at a stop or point of interest. Piedra Road is a busy road, so be careful and considerate. The accompanying map shows the local features and the major geological formations along the trip route. The map symbols, such as **Kmv**, refer to the geological formations described in the trip log. A large-scale geological map of this part of Southwest Colorado is available from the United States Geological Survey in Denver or on the internet (Steven, T.A., Lipman, P.W., Hail, W.J., Jr., Barker, Fred, and Luedke, R.G., 1974, Geologic map of the Durango quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-764, scale 1:250,000). The chapter **Pagosa Country Geologic History: the Table** includes a detailed outline through time of Pagosa's geology and list of references.

Fern growing in the Dakota Sandstone, Piedra River Canyon at Dead Man's Curve overlook (Mile 15.1)

ICE CAVE RIDGE – ROAD & TRAIL TRIP LOG

Miles	Points of Interest and Driving Instructions
0	**SET YOUR TRIP ODOMETER TO 0 AT THE TRAFFIC LIGHT AT HIGHWAY 160 & PIEDRA ROAD. Mile markers along Piedra Road are not always there! Turn onto Piedra Road (County Road 600) and continue to the north.** The first 1.6 miles of road travel take you across soil, gravel and other sediment deposited as the last of the Ice Age glaciers melted and the floodwaters carved and scoured the landscape. Almost all of today's landforms- hills, plains and cliffs- are the result of that period of glacial advances and retreats, and the intermittent massive floods, that lasted from about 100,000 to about 12,000 years ago. Before that time, between 1 and 3 miles of rock and sediment covered this area, and it was all ground and scoured away by the action of ice and water. Erosion today is proceeding at a much slower rate, because there simply isn't as much running water in today's drier, hotter climate.
1.6 Map symbol **Kdb & Kml**	The accompanying map shows the geologic formations exposed along the trip route, using standard geologic map colors and symbols (such as **Kml**). These symbols are shown in the mileage column to the left, to help you connect the trip log with the geology on the map and on the ground. The colors on the map identify the area where each rock type is exposed. The first letter in the symbol stands for a geologic age or period, such as **K** for **Cretaceous**; the remaining letters stand for the name of the geologic formation or material, such as **db** for the **Dakota Sandstone-Burro Canyon Formation**. This format is followed through the trip log below. The road crosses a landscape of Dakota Sandstone-Burro Canyon Formation (**Kdb**, which will be called "Dakota" in this log) and Mancos Shale. The 100-million-year-old Dakota Sandstone forms the floor of the wide valley. The orange-brown color of the stone and the soil that forms from it is the result of oxidation (rust) of the iron contained in the sandstone. Freshly broken stone is gray or white. The Dakota supplies most of the building and decorative stone used in the Pagosa area. The Dakota was laid down as sand and silt along the shifting shoreline as the Cretaceous Western Interior Sea was opening and spreading across the land. The widening sea gradually drowned the Dakota-age river deltas and swamps and beaches. As the land was submerged, the sediment being deposited changed from sand and silt to ocean-bottom mud of the Mancos Shale. It is this difference in sediment type which allows geologists to read changes in the ancient environment from the rocks formed in them. The transition from sandstone to shale marks the end of the land and beginning of the sea in this area (a time that geologists call a **transgression**), and provides a standard way to divide the rock formations. The Dakota weathers in roughly rectangular fragments because of joints (fractures) in the rock. These joints are the result of mountain-building forces which fractured the brittle sandstone. Erosion has stripped away most of the softer overlying Mancos Shale and left a wide, flat valley of pine forests and well-drained soil. The road climbs and sinks along the fringes of Mancos Shale hills and flat layers of Dakota Sandstone. The Mancos Shale lies above the Dakota and is locally mapped as the **Lower Mancos Shale** (**Kml**) and **Upper Mancos Shale** (**Kmu**). It was deposited on the floor of the Cretaceous Inland Sea that covered this area some 90 million years ago. The shale weathers into soft rounded hills and dry, steep slopes, with poor soil development. It erodes into fine clay which makes wet-weather driving such an adventure. The dark gray color is from abundant carbon, the remains of plants and animals which died and settled to the ocean floor.

	The Mancos Shale is about 2,000 feet in maximum thickness, representing possibly 20 million years of slow deposition. Mud accumulated at the rate of 1 inch every thousand years, except for rare events when storms or floods on land flushed sand into the sea basin. In its dark layers can be found ammonites (coiled shells up to 3 feet across), fish scales and teeth, oyster and clam shells, and other fossils of vanished marine life. These indicate that the sea was relatively shallow (200 to 300 feet deep) at times. The very thin, even layers show that the sea bottom was calm, with few burrowing animals to disturb the fine mud and clay that filtered down from above. The dark color comes from the carbon of millions of dead microscopic animals and plants; the decay of all this organic material robbed the bottom waters of their oxygen, leaving the lower sea water stagnant and dead. After the clay was cemented into rock, it was fractured and broken by later mountain-building to the north, and the fractures were filled by other minerals such as clear or white calcite and gypsum. In the road cuts, you can see the thin regular layers in the dark shale.
4.2 **Kdb**	The road now descends into the valley ahead, with exposures of blocky orange Dakota Sandstone on either side. The floor of the valley is a thin layer of Mancos Shale eroding from a basement of Dakota, which pops through here and there along the road and across the valley floor. Streams such as Dutton Creek are lined with "cliffs" of Dakota Sandstone, resembling mini-Grand Canyons no more than a few feet deep.
4.5 **Kml**	Just across Martinez Creek is a low hill to the right of the road, exposing bright gray Mancos Shale. This hill is held up by a dike (an igneous intrusion where magma was forced upward along a fault, creating a thin near-vertical "wall" of igneous rock). Almost nothing of the dike itself is exposed. To the south of Pagosa Springs along Highway 84, numerous dikes of the same age are well exposed and can be seen from the highway.
6.4 **Kml**	The road crosses a fault line, where the north side has dropped relative to the south side, but there is little obvious expression of the movement. Erosion has leveled both sides of the fault line. Just ahead, the paved portion of the road ends and the road becomes Forest Road 631. **The road is gravel from here to the end; drive carefully and observe the posted speed limit.** Dust and flying gravel are real hazards.
6.9	The road climbs a steep hill, probably another fault line. Faults within the Mancos Shale are difficult to identify; this may simply be an erosional slope.
10.5 **Kml**	Ahead is a conical shale hill called the "Ant Hill". The mountains ringing the horizon beyond are the remains of huge volcanoes, part of the San Juan Volcanic Field that erupted intermittently from about 40 million to about 10 million years ago. At about 28 million years ago, the pressure of the rising magma caused a massive volcanic eruption, the largest known on Earth so far, called the La Garita Caldera eruption. This blast threw over 1,500 cubic miles of rock and dust and lava into the air, excavating a hole 70 miles across from north to south and 45 miles wide from east to west. The southern margin of this huge crater, larger than Mineral County, is today's Continental Divide, the San Juan Mountains a Wolf Creek Pass. The entire Four Corners area was buried in thick layers, possibly a mile deep, of volcanic debris after this eruption. From that day, over the next 10 million years, smaller volcanoes continued to erupt, burying the crater with later volcanic rock, and today there is little visible evidence of this monstrous eruption.

	From about 10 million years to about 1 million years ago, the heat beneath the Colorado Plateau has been fading, ending the cycle of volcanic eruptions. Volcanic eruptions gradually subsided and generally ceased about 10 million years ago. The Pagosa and other hot springs are the last remnants of this volcanic energy.
13.5 **Kmu**	The road has climbed into the Upper Mancos Shale, a lighter-colored part of the formation. Notice the hills with steep bright-gray eroded faces to the right of the road. This dry and barren surface is the natural habitat of the frosted bladderpod (*lesquerella pruinosa*), an endangered plant that is limited to these inhospitable exposures. Ahead, the road runs close to the edge of a deep canyon. This is the Piedra River canyon, bounded for a short distance by the vertical cliffs of the Dakota. This is the rock layer that hosts the Ice Caves. The river sliced through the hard sandstone powered by the floods of the melting glaciers; today's shrunken stream has little ability to deepen or widen its course. Most erosion along the canyon today is the result of freeze-thaw expansion and contraction, which splits the rock from the canyon walls.
15.1-15.4 **Kdb**	Two pullouts along the left side of the road provide spectacular views of the canyon. This is "Deadman's Curve", named for obvious reasons! The parking areas are on the top of the Dakota Sandstone. Note the bright sparkly surface of the weathered rocks- this stone is cemented by quartz rather than sofer calcite, making it much harder and more crystalline.
16.2 **Kml**	**<u>CROSS THE PIEDRA RIVER BRIDGE AND TURN LEFT</u>** into the Piedra River Trailhead parking area. From here, the remainder of the trip is a walking tour. The foot trail rises from about 7,740 to 8,000 feet in elevation over about 3/4 of a mile. <u>SAFETY WARNING:</u> ***This is a hazardous area. If you choose to continue, please stay on the trail and keep dogs on leash. Open ice caves my be concealed by pine debris or winter snow.***
Qd	**<u>At the trailhead:</u>** Look to the mountains. These are the southern edge of the San Juan Volcanic Field, vast thick layers of lava and ash blown out 28 million years ago in one of the largest volcanic explosions known to geologists. Imagine a mountain as large as Mt. Fuji or the highest peaks of the Andes superimposed behind these that you see- and now imagine in one explosion this mountain disappearing. The explosion threw some 1,500 cubic miles of debris into the sky at 1,500 degrees C (2,100 degrees F), which fell across the Four Corners area in a blanket 1/2 mile thick or more. Where you stand now was a wasteland- nothing survived. The Ice Age glaciers and floods have removed the volcanic debris and exposed the ancient mud of the Mancos Shale again; in geologic terms, they were buried for only the blink of an eye. The trailhead parking area sits atop a thin veneer of Quaternary age glacial debris (**Qd**) that hides the shale. **Follow the trail to the right.**
Qd	**<u>At the trail split:</u>** Imagine that there is a glacier as tall as the mountains beyond, and you are standing at its base. From 1 million to about 18,000 years ago there were such glaciers here, scraping, carrying and pushing rock as the ice moved downhill. The rock and plant debris caught up with it were ground and crushed and finally left behind when the ice melted away, in deposits called glacial moraines (**Qd**). You are standing on one such moraine.

	Notice the cottonwood trees, growing high on the slope. Cottonwoods need a steady supply of water to survive, yet these trees thrive far above the river. Glacial moraine deposits are made of a wide mix of material from boulders to fine clay; this mix is highly porous and carries a great deal of water through their open spaces, feeding these thirsty trees. **Follow the two-track trail up toward the trees** (the lower trail heads down into the Piedra River Canyon and provides a fascinating look at the base of the Dakota along the canyon floor).
Qd	<u>Glacial Erratics:</u> The boulders you see here are glacial erratics, large rocks left behind when the last glaciers melted. These boulders probably traveled hundreds of miles within the glacial ice to end up here. The grinding and force of the ice rounded the rocks and polished their surfaces. There were at least four major pulses of glaciation between 1 million and 18,000 years ago. Between periods of glaciation, the climate warmed and floodwater filled a wide river channel here, surrounded by cold marshes and numerous thermal vents. The ecosystem was similar to today's Yellowstone National Park. Periodically ice dams would form and hold back small and large lakes; when these dams melted and failed, blocks of ice the size of apartment buildings tore down the engorged river, destroying everything in their path. It was a time of extreme ecological diversity. There were vast numbers of migratory birds, herds of bison, early horses, and perhaps caribou and mammoths. Large predators such as the cave bear and the dire wolf, and possibly the American lion and saber-tooth cat, stalked the herds.
Kdb	<u>Dakota Sandstone:</u> Notice the different quality and color of the trail here- it is no longer made up of gravel and broken volcanic rock, and instead is floored with fine sand and sandstone fragments. You have just stepped back in time. The trail has crossed from glacial moraine sediment to the eroded surface of the Dakota Sandstone. The Dakota was deposited as the shallow inland sea was beginning to flood the land, gradually inundating much of the southwest from Canada to Mexico. The rock layers are the delta and tidal flat sands and gravels that you can see today in any major river-beach-sea floor environment. Dinosaur bones, teeth, fish scales and other fossils testify to the abundance of life along this rich shoreline. The sediments piled up about 450 feet thick before the sea took its place, replacing the sands and gravels with the thin slow accumulation of sea-floor mud- the Mancos Shale.
Kdb	<u>Aliens among us:</u> In the spring, this field is bright with yellow-flowering plants. The vista is visually appealing at first glance. However, it represents an insidious outbreak of an invasive weed called yellow toadflax (*linaria vulgaris*), also known as "butter-and-eggs". With vigorous growth, an extensive root system, and aggressive seed-dispersal ability, it easily displaces native grasses. This results in a loss of food and habitat for native animal species and thus reduces ecological diversity. Brought to the United States as an ornamental (garden) plant from Europe, it has no local insects or diseases to control its growth; once established, it is virtually impossible to eradicate. To limit the spread of this and other such weeds, County and Forest Service regulations require stock feed and all plant seed mixes to be certified as weed-free.

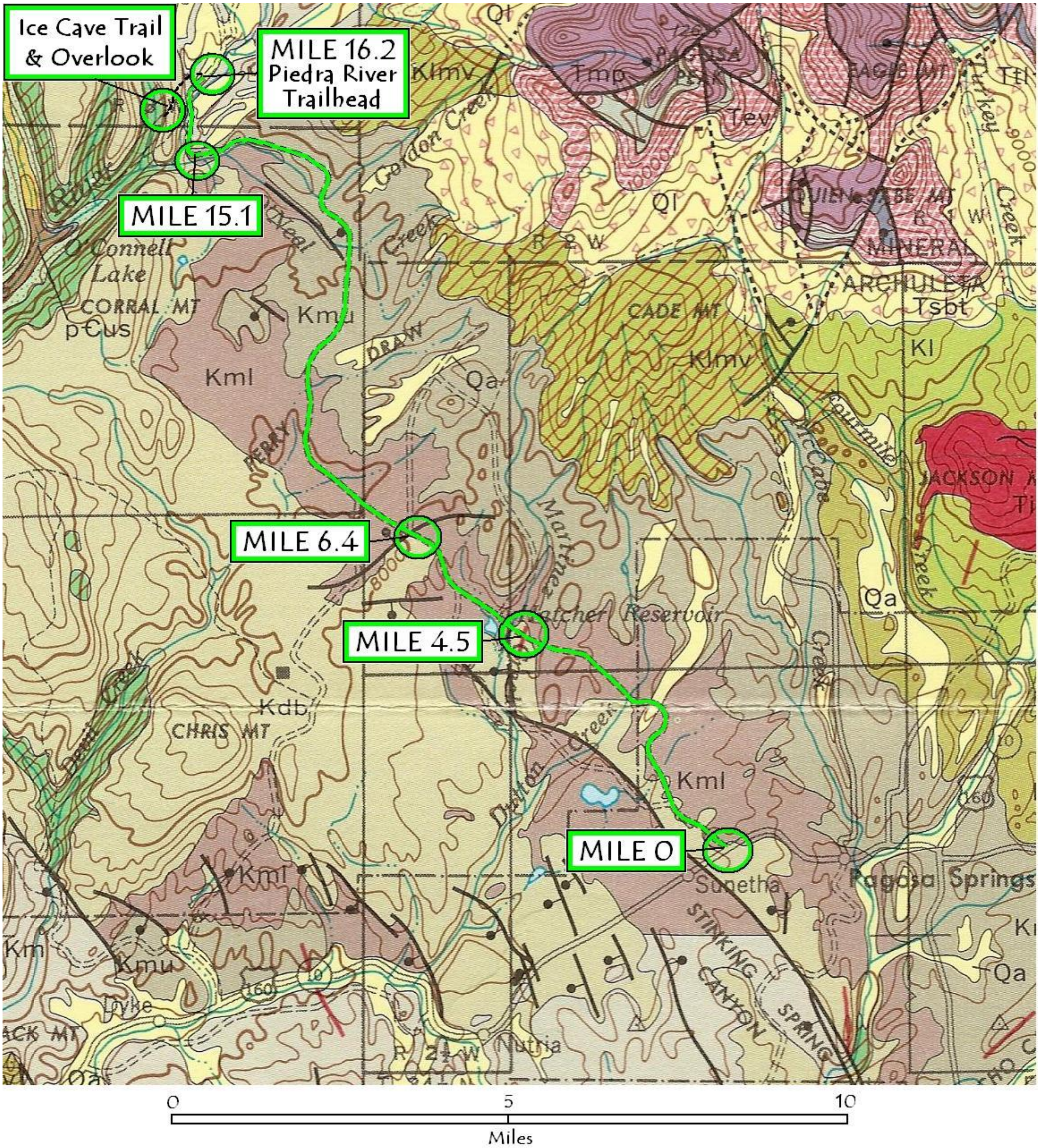
Kdb	<u>Mossy glade:</u> The deep green moss and ferns in this forest opening indicate a profusion of water below the surface. The Dakota Sandstone is porous and fractured; as snow and rain settle on the ridge uphill, these fractures capture the moisture and channel it downhill. This underground flow keeps the soil moist and feeds many springs that in turn supply the Piedra River with water.
Kdb	<u>Animal tracks:</u> Can you see evidence of animal activity here? Trees may show claw scratches and stripped bark (bear claws?), or holes drilled by birds. Other traces, often the only sign an animal has passed this way, may be tracks, scat, fur and feathers, nests and burrows.
Kdb	<u>Detached Dakota:</u> This angled block of detached Dakota Sandstone has slid down from its original location on the ridge above. Several million years from now, it will end up in the Piedra River- also the ultimate fate of the Ice Caves themselves. Here's why: the Dakota Sandstone was deposited on top of the Morrison Formation, the last rock layer laid down during the Jurassic Period some 150 million years ago. The Morrison is a sequence of floodplains and river deposits, swamps and alkaline lakes- with a high content of clay, soft and weak as rocks go. The overlying Dakota is thick, hard and brittle, heavier than the rock below, and as the land was tilted by mountain-building forces to the southeast, the Dakota is being pulled by gravity downslope. As erosion of the softer rock below by the Piedra River slowed, though, an uneasy balance has prevailed and the main caprock of the Dakota remains in place. However, a return of a wetter climate will cause the rock to move again.
Kdb	<u>Weathering- the force of Nature:</u> Nature does not admire heights or depths. Gravity drives all things downward, to smooth over the heights and fill in the deeps. Chemical and physical forces also conspire to break the rock down into smaller particles. See how many processes you can discover in this block of sandstone. **Chemical weathering:** Moss and lichen growing on the rock surface and roots invading the microscopic pores and fractures secrete organic acids that literally dissolve the rock into its mineral components. Acid rain and groundwater, which is naturally acidic in this area, dissolve the silica (quartz) cement between the sand grains, creating weak areas along the fractures and widening the natural pore spaces, which in turn allows more water in to further this destruction. Notice areas where the sandstone surface appears "melted". **Physical weathering:** Plants grow in the fractures and their roots can exert enough pressure to break the rock apart. Water entering a crack of any size will freeze and thaw, further widening the fracture. Gravity pulls on the rock's mass, weakening it and unbalancing it, widening cracks and providing pathways for more water and plant roots to do their work. Eventually the rock is reduced to soil.

Kdb	<u>Dakota Deposition:</u> This sandstone was not deposited in a single 400-foot event. It was laid down in a long series of depositional events over millions of years. At times the sand was deposited quietly in still waters; at other times the turbulent current drove layers of granules and pebbles to form a conglomerate layer. Smooth flat sheet-wash layers only an inch thick alternated with thick layers of rippled sands where the tides bore in and out. As a result, the Dakota Sandstone has layers within it that tell the story of when and how the environment of deposition changed. Certain types of plant and animal fossils, mud cracks, ripple marks, raindrop impressions, and sole markings (where something was dragged across the soft muddy bottom of the sea) all tell their tales. At the boundary of each layer, the rock is poorly bonded, creating a zone of weakness. Look at the large sandstone blocks along the upper side of the trail. Notice that ferns preferentially grow at the obvious boundary between layers. As you walk ahead on the trail, look for evidence of these changes in the paleoenvironment.
Kdb	<u>Sands of Time:</u> Over time, all rock crumbles. Most rock is reduced to sand- quartz grains, smoothed and rounded by weathering and abrasion. The sand here is freshly weathered from the Dakota Sandstone. Notice the glitter in the sun- this indicates the presence of crystal faces; these angular grains have not travelled far enough to be smoothed and rounded, showing that their source, their parent rock, is close at hand.
Kdb	<u>Mud Clasts:</u> As floods washed across the river bed, the force of water gouged up balls of mud and deposited them downstream. Sandy sediment was deposited on top of these mud clasts, and over time the sediment was cemented into rock. The mud clasts, once exposed by weathering, melted away, leaving spherical holes in the rock. Look at the surfaces of the sandstone blocks along the trail. These remnants of the ancient river bed show the holes from flood-deposited mud clasts. Mud clasts are important indicators of paleoclimate. The size and orientation of clasts gives information about the energy and stream flow character of the ancient river.
Kdb	<u>Historic Forest Use:</u> A fence line crossed the trail once, harkening back to a time when this land was privately owned and ranched. In the recent past, the land was exchanged to the Forest Service for public land down the valley, now part of the Piedra Valley Ranch. Such land exchanges allow the Forest Service and other land agencies to acquire land for the public interest while disposing of lands that do not meet the agency's mission.
Kdb	<u>Sole Marks:</u> Another important indicator of paleoclimate is sole marks, the fossilized evidence of underwater activity. Watch the middle of the trail for a flat triangular slab of rock with circular and linear marks on the surface. As noted above, these marks are evidence of how the layer of sediment was deposited and the energy of the environment. Observe these markings: what activities do you think they represent? What could have made them?

Kdb	**Ice Caves:** You have reached the first ice cave. Less a cave than a long linear fracture, it continues for hundreds of feet both vertically and horizontally. This opening has most likely been enlarged in the past so that settlers could retrieve ice from the fracture; thus the name "ice cave". How were the caves formed? In a nutshell, brittle stuff breaks. The hard and brittle Dakota Sandstone was deposited flat across the slippery Morrison Formation clay and mud. Due to later volcanic and tectonic forces, the brittle Dakota fractures in north-south and east-west trending lines. Following the titanic pressure that built the Rocky Mountains, the once-horizontal layers of rock were tilted slowly to the southeast. Later, during the glacial period, floods followed these lines of weakness, draining the rising land down to the south and deepening the natural fractures. Once the raging streams broke through the hard Dakota to the much softer Morrison layers beneath, the drainages deepened to narrow parallel canyons bounded by near-vertical cliffs, capped by hard fractured Dakota Sandstone mesas. Throughout this time, gravity was pulling the Dakota to the south. As millions of years of rain and snow saturated the fractures, this constant pull caused the sandstone to detach from the shales below, shifting the rock and widening the fractures. Erosion in the river canyons ate away the supporting cliffs and the upper mesa rim rock fell. Near these precipitous edges, the Dakota caprock flexed downward, pulling the interior fractures further apart. Cut parallel slices in a rubber slab and bend the edges down- the slices will open upward. The ice caves were created just like this. Today the Dakota is in equilibrium, and the fractures are not measurably enlarging. But any change can disturb the balance and set the process in motion again. The existing fractures most likely extend through the entire thickness of the Dakota, some 400 feet; At depth, solid ice is preserved by the insulating rock throughout the year, but it is largely inaccessible. The settlers mined the ice across these mesas, often at perilous depth, but today the ice caves are simply a beautiful and curious wonder of nature. The constant cool moisture feeds forests of ferns and mosses that cling to the vertical walls, and the deeps are filled with fallen trees and forest debris among the layers of snow and ice. If you continue up the trail to the canyon rim overlook, watch for north-south and east-west trending depressions that look like filled-in ditches. These are unopened "ice caves".
	SAFETY WARNING: ***This is a hazardous area. If you choose to continue, please stay on the trail and keep dogs on leash. Open ice caves my be concealed by pine debris or winter snow.***
Kdb	**At the Overlook:** Look across at the opposite canyon wall. Notice the rock layers, and imagine the titanic forces of gravity pulling those rocks down. Look at the thick rubble at the base of the cliff- that is mostly broken Dakota Sandstone caprock that has succumbed to gravity's grasp. The cliff edge today is relatively stable; barring a major seismic event, collapse of the edge will be limited to small fragments broken loose by heat-cold expansion. But now and then, a huge segment may give up the fight and slide into the depths, carrying its forest cover with it. Nature never rests, and the steep canyon walls are an affront to gravity. Enjoy them while they stand because they will not stand forever; in a geologic second of time, they will be no more.

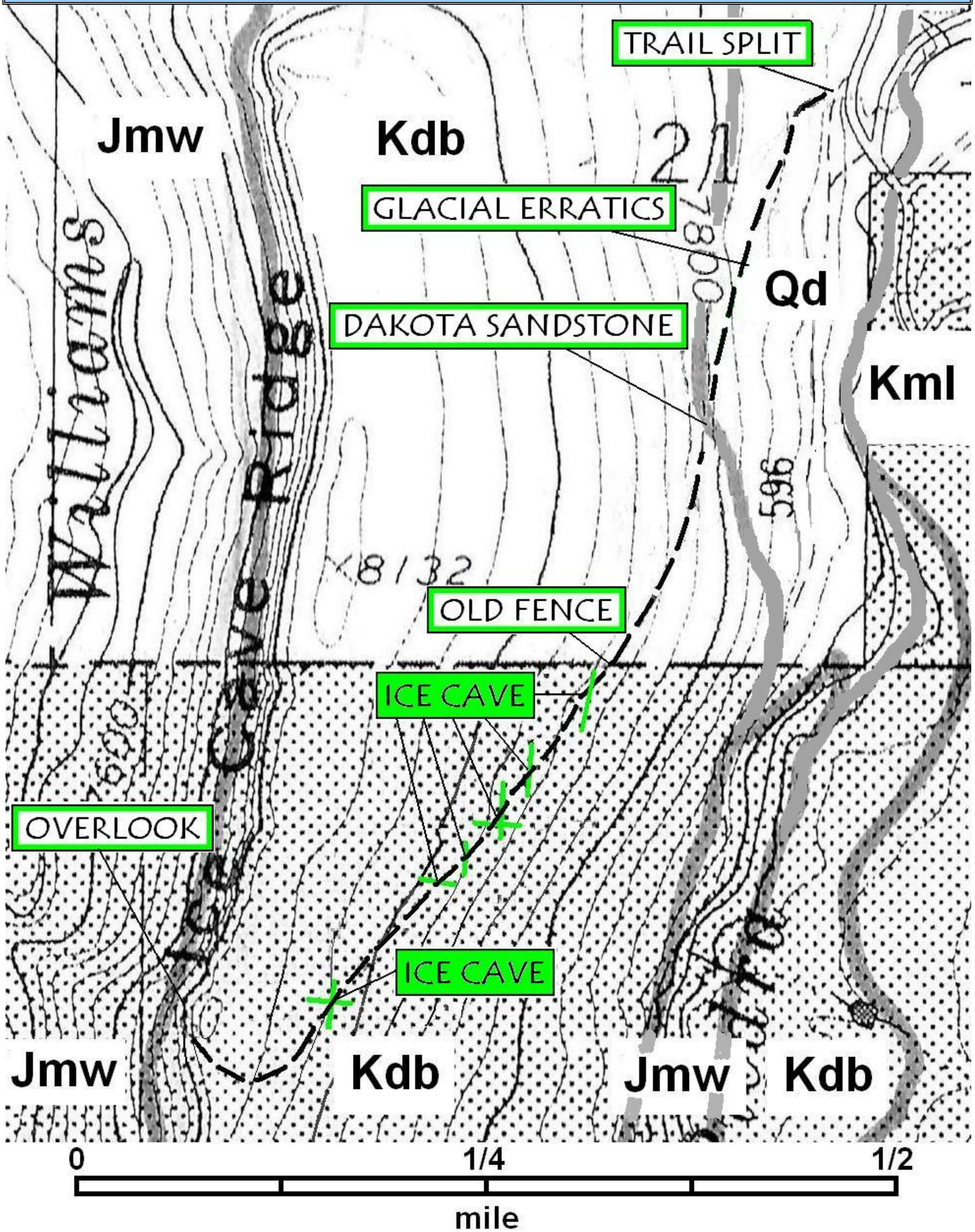
Ice Cave Ridge: *Geologic Map*

From Steven and others, 1974



Contour interval 200 feet. See geologic map key at end of document.

Ice Cave Ridge: *Trail Map*



GEOLOGIC MAP UNITS NOTED IN ROAD LOGS

From Steven and others, 1974

Qa | Qd — **ALLUVIAL AND GLACIAL DEPOSITS (QUATERNARY) –** Alluvium, terrace gravels, and alluvial fan deposits; glacial debris and moraine deposits.

Ql — **LANDSLIDE DEBRIS (QUATERNARY).**

Ten — **EARLY INTERMEDIATE LAVAS AND BRECCIAS (OLIGOCENE AND OLDER?; 31.1 – 34.7 million years old) –** Near-source facies – mostly flows and breccias of aphanitic to prominently porphyritic andesite and rhyodacite from many centers. Some dark andesites contain prominent thin tabular plagioclase phenocrysts. More silicic fine-grained to coarsely porphyritic quartz latite and rhyolite occur locally.

Tev — **EARLY INTERMEDIATE LAVAS AND BRECCIAS (OLIGOCENE AND OLDER?; 31.1 – 34.7 million years old) –** Volcaniclastic facies – mostly reworked, bedded conglomerates, sandstones, and mudflow breccias of dark andesite and rhyolite clasts.

Tfg — **FISH CANYON TUFF (OLIGOCENE; 27.8 million years old) –** Ash-flow tuff of biotite-hornblende-plagioclase quartz latite with minor quartz and sanidine containing about 50 percent phenocrysts. Sparse resorbed quartz and accessory sphene phenocrysts are distinctive. La Garita caldera.

Tmp — **TUFF OF MASONIC PARK (OLIGOCENE; 28.2 million years old) –** Biotite-pyroxene-plagioclase quartz latite ash-flow tuff containing 50-60 percent phenocrysts. Mount Hope caldera.

Ts — **SNOWSHOE MOUNTAIN TUFF (OLIGOCENE) –** Red-brown biotite-pyroxene-quartz latite ash-flow tuff containing 35-60 percent phenocrysts, mainly plagioclase, biotite, and augite. Creede caldera.

Tcd — **CREEDE FORMATION (OLIGOCENE) –** Stream, lake, and pyroclastic deposits containing widespread travertine within Creede caldera.

Ti — **INTRUSIVE ROCKS (AGE OF EMPLACEMENT NOT KNOWN)** – Heterogeneous intermediate to silicic hypabyssal intrusive rocks with a wide range in textures and compositions. Generally between 10 and 30 million years old; dikes range from tens of feet wide down to invisible, following fault lines that generally run north-south; most hill crests are dikes.

TKa — **ANIMAS FORMATION (PALEOCENE AND UPPER CRETACEOUS)** – Dark varicolored sandstone, shale, and conglomerate; contains abundant volcanic and arkosic detritus; maximum thickness about 2,700 feet. Generally between 58 and 66 million years old; debris washing from rising volcanic mountains (ancestral Rocky Mountains) into shallow sea basin buried the swamps of the Fruitland Formation.

Kkp — **KIRTLAND, FRUITLAND, AND PICTURED CLIFFS FORMATIONS (UPPER CRETACEOUS).**
KIRTLAND & FRUITLAND FORMATION – Lenticular beds of sandstone, shale, and coal; maximum thickness about 400 feet. Generally between 66 and 68 million years old; Kirtland and Fruitland Formations are the remains of widespread swamps (mud flats, floodplains, tropical forests and peat bogs, with shallow clam and oyster flats) that filled the shallow sea basin of the Lewis Shale. The Fruitland Formation contains valuable coal and natural gas deposits.
PICTURED CLIFFS FORMATION – Light-gray sandstone interbedded with dark-gray shale in lower part; maximum thickness about 300 feet. Generally between 68 and 72 million years old; Pictured Cliffs Formation is made up of beach sands, tidal flats and deltas of the western shoreline of the ancient Cretaceous Inland Seaway that stretched from Mexico to Canada, bisecting North America. Fossils of palm trees, ferns, and dinosaur bones occur along with burrows of sand crabs and petrified beach dunes. The name derives from Indian rock art on cliffs in New Mexico.

Kl — **LEWIS SHALE (UPPER CRETACEOUS)** – Dark-gray clay shale; contains thin sandstone beds near top, and rusty-weathering concretions in lower part; maximum thickness about 2,700 feet. Generally between 72 and 90 million years old; The Lewis Shale is made up of stagnant sea-floor mud and clay, with fossils of sea creatures (clam and oyster shells, ammonites, fish teeth and scales); Thin beds of sandstone represent major floods which washed sand deep into the sea basin; these sand layers preserve roots and burrows of shallow sea-floor plants and animals, and exhibit ripple beds formed by the strong flood currents.

Kmv — **MESA VERDE FORMATION (UPPER CRETACEOUS)** – Interbedded thin sandstone and dark-gray shale; minor carbonaceous shale and coal; maximum thickness about 350 feet. Generally about 90 million years old; the Mesa Verde Formation is made up of shoreline deposits (beach dunes, tidal flats, lagoons, backwater floodplains and swamps) deposited during a short period when the seas retreated from this area.

Km **MANCOS SHALE (UPPER CRETACEOUS)** – Mostly dark-gray marine shale; maximum thickness about 2,400 feet. Generally between 90 and 100 million years old; the Mancos Shale is made up of stagnant sea-floor mud and clay, with fossils of sea creatures (clam and oyster shells, ammonites, fish teeth and scales); thin beds of sandstone represent major floods which washed sand deep into the sea basin; these sand layers preserve roots and burrows of shallow sea-floor plants and animals, and exhibit ripple beds formed by the strong flood currents. The ancient organic material, leached out by heated ground water, provides the minerals for the Pagosa Hot Springs thermal baths.

Kmu Upper part – Contains calcareous shale and argillaceous limestone (Niobrara Formation equivalent) in lower 600 feet, and has sandy limestone and argillaceous sandstone (Juana Lopez Member) at base; maximum thickness about 1,900 feet.

Kml Lower part – Contains thin calcareous shale and limestone (Greenhorn Limestone equivalent) in lower 150 feet; maximum thickness about 500 feet.

Kdb **DAKOTA SANDSTONE AND BURRO CANYON FORMATION (UPPER AND LOWER CRETACEOUS)**
DAKOTA SANDSTONE – Light-gray to brown sandstone with Interbedded siltstone and carbonaceous shale; commonly contains chert pebble conglomeratic sandstone at base; Dakota Sandstone disconformably overlies Burro Canyon Formation. There is a moderate potential for the occurrence of economic deposits of oil in the Dakota Sandstone, though no reserves have been proven in the Pinon Hills Ranch area.
BURRO CANYON FORMATION – Lenticular chert-pebble conglomerate interlayered with green and gray claystone. Maximum thickness of the combined formations is about 300 feet. Generally between 100 and 145 million years old; Dakota/Burro Canyon are tidal flat and shallow sea-floor deposits with numerous marine fossils. Most of the decorative stone in this area is the Dakota Sandstone, which forms the surface rock of most of the Pagosa Lakes area.

Jmw **MORRISON AND WANAKAH FORMATIONS (UPPER JURASSIC)**
MORRISON FORMATION – **Brushy Basin Member** is mostly varicolored claystone and mudstone; it overlies the **Salt Wash Member** which is mostly sandstone with Interbedded claystone and mudstone; Brushy Basin deposits are swamps and floodplain debris; Salt Wash deposits are river channel and delta deposits. The Morrison Formation contains abundant dinosaur fossils, such as at Dinosaur National Monument, and valuable uranium ore.
WANAKAH FORMATION – Junction Creek Sandstone Member is light-gray cross-bedded sandstone; **Pony Express Limestone Member** is dark-gray bituminous limestone that locally contains gypsum. Maximum thickness of the combined formations is about 800 feet. Generally between 145 and 150 million years old.

Contact between geological formations

Fault – bar and ball on downthrown side