FIELD TRIP GUIDEBOOK ON THE GEOLOGY AND GEOLOGIC HAZARDS OF THE GLENWOOD SPRINGS AREA, COLORADO

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INTRODUCTION

The Glenwood Springs area geologic field trip for the 1996 national meeting of the Geological Society of America focuses on the late Paleozoic Eagle Basin, late Laramide White River Uplift, and Neogene tectonism, volcanism, and geomorphic history. Active geologic processes and their relation to works of man will be discusssed. On route to the Eagle Basin we will cross the structurally deepest part of the Denver Basin, the Laramide Front Range Uplift, a half graben related to the Neogene Rio Grande Rift, and the Neogene Tenmile and Gore Ranges (Figure 1). Our first stop is at Vail Pass about 136 km (85 miles) from downtown Denver. A description of the geology along the route from Denver to that stop is included in the guidebook.

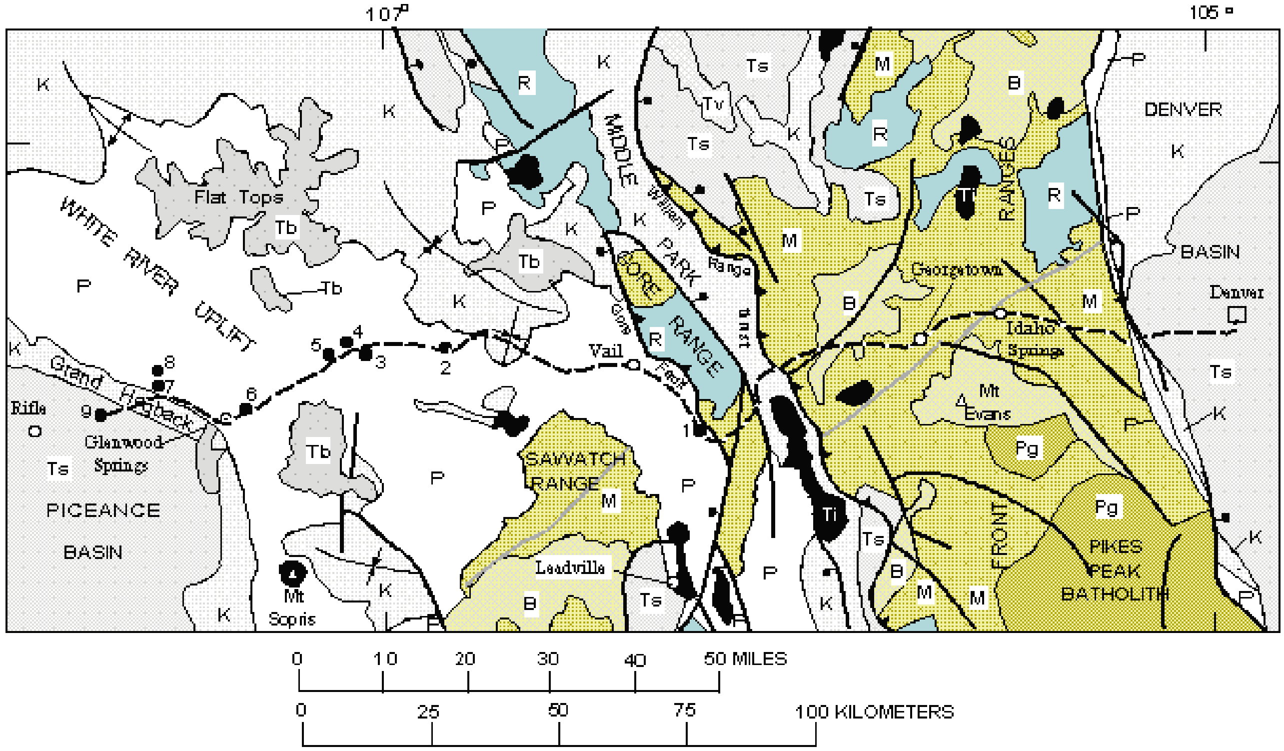
The Colorado Geological Survey (CGS) and U.S. Geological Survey (USGS) are cooperatively mapping in the region. Since their work is in progress, interpretations presented herein should be considered as working hypotheses and subject to modification. We hope that the field trip stimulates questions and discussions which will aid our geologic studies of this fascinating area. The summary of regional geology that follows is modified from Bryant and Beaty (1989) and Reed and others (1988).

REGIONAL TECTONICS

Today central Colorado is part of a large topographic high named the Alvarado Ridge by Eaton (1986), who attributed its origin to Neogene tectonism: coeval lithospheric thinning, extensional strain, and differential vertical jostling along the crest of the ridge. Age of this topographic high has been questioned by Gregory and Chase (1992) and Gregory (1994) based on the interpretation of leaf morphology in late Eocene and early Oligocene floras from deposits at high altitude in central Colorado. They interpret those deposits to have been laid down at essentially the same altitude as they are today, in contrast to the earlier paleobotanical interpretation by MacGinitie (1953) who proposed substantial regional Neogene uplift. In any case, the Rio Grande Rift extends along the crest of the Alvarado Ridge through New Mexico and Colorado, and it is closely related structurally and temporally to regional extension in the Basin and Range Province to the west.

Direct evidence of Neogene tectonism near Glenwood Springs includes various faulted and folded Neogene deposits; indirect evidence includes presence of Neogene igneous rocks and extrusive centers, geomorphic development of major canyons, and extensional style of faulting. Major tectonic features in the Glenwood Springs area are shown in Figure 2.

The 1,000-km long Alavarado Ridge is superposed on a long succession of pre-Neogene structures. The youngest of the structures upon which the Neogene tectonism is superposed are Laramide uplifts, of which the Front Range is an example, formed on the craton in front of the Cordilleran fold and thrust belt in Late Cretaceous and early Tertiary time (70–40 Ma). Previous workers disagreed on whether these uplifts were formed by horizontal compressive forces or vertical forces. Seismic exploration and drilling (Gries, 1983) and COCORP reflection profiling (Smithson and others, 1979; Brewer and others, 1982) show that major faults bounding the uplifts are thrust faults that carry rocks of the uplifts over adjacent basin fill. In a regional analysis of the history of Laramide sedimentary basins, Dickinson and others (1988) concluded that the intricate geometry of Laramide uplifts and basins developed in a generally synchronous strain field imposed over a region of heterogeneous crust. What caused this strain field to form? One interpretation is that in Late Cretaceous and early Tertiary time North America overrode buoyant oceanic lithosphere along a gently dipping subduction zone (Hamilton, 1988). Because of drag against the overridden slab, the southwestern United States advanced slightly more slowly than the continental interior, resulting in a broad zone of crustal shortening. The regional pattern of the structures formed by compression indicates that the Colorado Plateau region has rotated a few degrees clockwise around a Euler pole near central New Mexico relative to the continental interior. Somewhat different plate tectonic interpretations have been proposed by Chapin and Cather (1981), Gries, (1983), and Cross (1986). Laramide



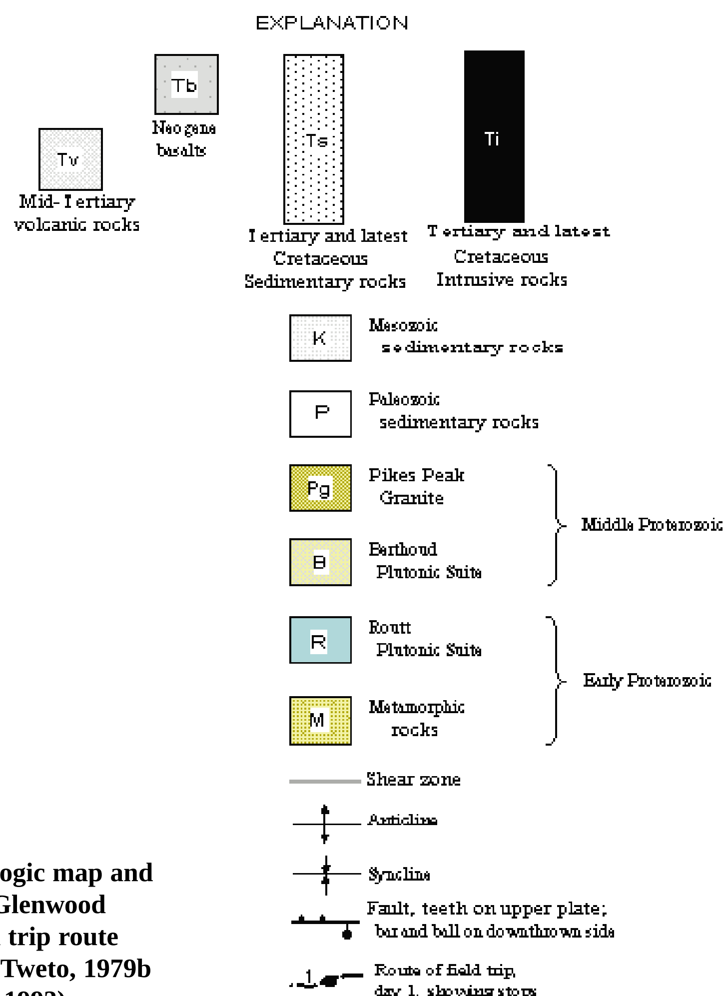


Figure 1. Generalized geologic map and route from Denver to the Glenwood Springs area showing field trip route and stops on Day 1. (after Tweto, 1979b and Aleinikoff and others, 1993)

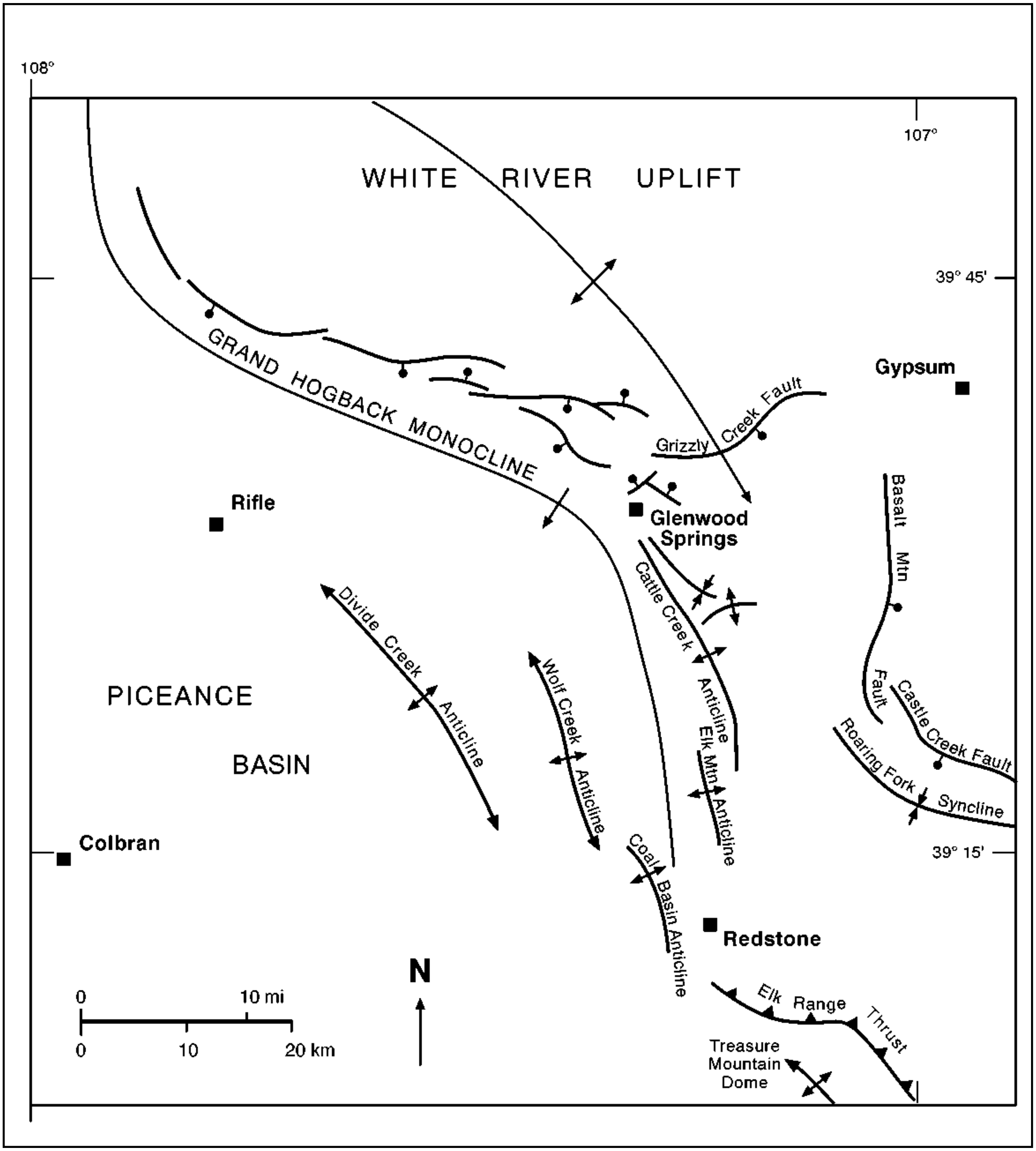


Figure 2. Regional tectonic map of the Glenwood Springs area. (after Tweto, 1979; Bryant, 1979; Grout and others, 1991; and Kirkham and others, 1995, 1996)

structures to be examined during the field trip include the Grand Hogback Monocline and White River Uplift.

The next oldest major deformation occurred in late Paleozoic time when northwest-trending mountain ranges (the Ancestral Rockies) and basins formed (Figure 3). The mainly clastic basin-fills are locally as much as 5 km thick and are well preserved in many areas, including Glenwood Springs. Much of these fills was deposited in a semi-arid climate, and iron-bearing minerals, such as magnetite and hornblende, were chemically altered to produce strikingly red rocks that give the State of Colorado its Spanish name. Kluth (1986) related the formation of these ranges and basins to the collision of the North America and South America-Africa plates during the Ouachita-Marathon orogeny. Near Glenwood Springs the Belden, Eagle Valley, and Maroon Formations were deposited during this orogeny.

The oldest recorded event in the region was the formation of continental crust in Early Proterozoic time when a series of arcs and interarc basins were formed and welded to the Archean craton (Reed and others, 1987; 1993). The rocks produced in this event form much of the mountains we cross before our first stop, and they also crop out in Glenwood Canyon, which we see on the afternoon of Day 1.

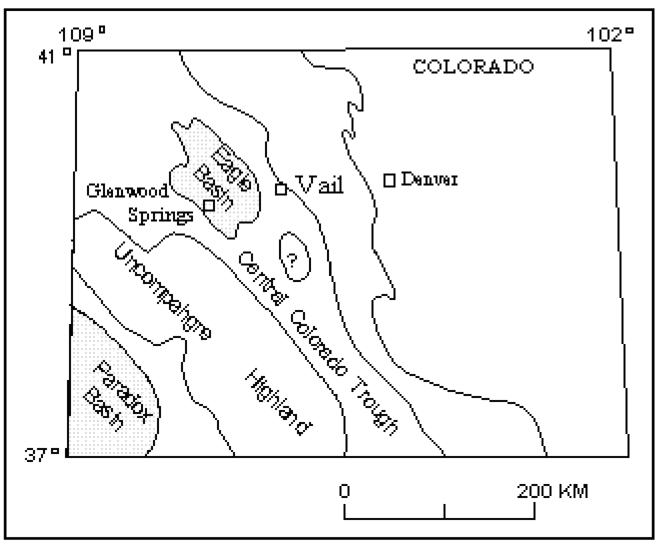


Figure 3. Late Paleozoic tectonic elements in Colorado. Areas of evaporite deposition patterned. (after Mallory, 1960 and De Voto and others, 1986)

PRECAMBRIAN ROCKS

The oldest rocks in central Colorado are supracrustal and plutonic rocks that are apparently products of arc-magmatism and sedimentation in arc-related basins along the southern edge of the Archean Wyoming craton. This extensive terrane was accreted to the craton over an interval of 130 m.y., beginning at about 1,790 Ma (Reed and others, 1987). Most of the supracrustal rocks are assigned to two general groups: 1) interlayered quartzo-feldspathic gneiss and amphibolite, and 2) interlayered biotite schist, gneiss, and migmatite. These rocks typically are metamorphosed to upper amphibolite-facies and are complexly deformed, commonly by several sets of superposed folds. The two groups are complexly interleaved, probably both structurally and stratigraphically. In southern Wyoming and south-central Colorado, less deformed and metamorphosed sequences of volcanic and volcaniclastic rocks are preserved, and general similarities in composition and proportions of felsic and mafic rocks suggest that many of the felsic gneisses and amphibolites are of metavolcanic origin. The biotitic rocks locally contain layers and lenses of marble, quartzite, and conglomerate, and in one area in northern Colorado biotite gneiss, schist, and migmatite of sillimanite grade can be traced into biotite- and chlorite-grade graywacke and pelite (Braddock and Cole, 1979). Thus the biotitic rocks are regarded as largely of sedimentary origin.

A variety of Early Proterozoic calc-alkaline plutons, chiefly granodiorite or quartz monzonite (monzogranite of Streckeisen, 1973), but ranging from peridotite to granite (syenogranite of Streckeisen, 1973), cut the supracrustal rocks. Many of these plutons are concordant and strongly foliated and are generally considered to be syntectonic. Other plutons are discordant and display only weak foliations. The plutons range in age from 1,780 to 1,650 Ma (Reed and others, 1987; Reed and others, 1993), and are commonly only slightly younger than their wallrocks. Concordant “syntectonic” plutons in places are younger than discordant “post-tectonic” plutons in other places, indicating that deformation and metamorphism were not synchronous throughout the region. Field evidence and isotopic ages demonstrate that deformation and metamorphism of the supracrustal rocks were nearly synchronous with emplacement of the plutons. This correspondence in age, the inferred high temperature-low pressure metamorphism, and the structural patterns around the major plutons led Reed and others (1987) to suggest that emplacement of the plutons was the leading cause of metamorphism and deformation. The difference between “syntectonic” and “post-tectonic” plutons is probably more a matter of crustal level of emplacement than of time of emplacement relative to a tectonic event. The Early Proterozoic plutons commonly have been referred to as “Boulder Creek” intrusives, however Tweto (1987) assigned the name Routt Plutonic Suite to distinguish them from the Boulder Creek Granodiorite of the Boulder Creek batholith, which is only one of the many diverse Early Proterozoic plutons.

Brief widespread mid-crustal reheating 1.4 Ga (Shaw and others, 1995; Selverstone and others, 1995) was accompanied by the intrusion of myriad dikes, stocks, and irregular discordant plutons of weakly foliated or non-foliated two-mica granite. These rocks, which were emplaced during a continent-scale igneous event at about 1,400 Ma (Anderson, 1983), have been called “Silver Plume Granite”. However, Tweto (1987) assigned these Middle Proterozoic rocks to the Berthoud Plutonic Suite and reserved the name “Silver Plume” specifically for the rock in the Silver Plume batholith, one of many plutons of that general age.

The youngest major group of Proterozoic igneous rocks in central Colorado comprises the 1,092–1,074 Ma (Unruh and others, 1995) Pikes Peak batholith. The batholith is principally biotite and hornblende-biotite potassic granite, but includes small plutons of syenite, quartz monzonite, alkali diorite, and related rocks. Geochemical data suggest that the rocks in the batholith originated by a combined process of fractional crystallization of alkali-basalt liquid and assimilation of granodioritic and granitic roof rocks. Emplacement may have been as shallow as 5 km (Barker and others, 1976).

Proterozoic rocks are cut by an anastomosing swarm of northeast-trending zones of ductile deformation and cataclasis. Histories of these shear zones are long and complicated, but movement along some began in the Early Proterozoic. A concentration of the zones in central Colorado apparently localized the Laramide and younger plutons in the Colorado mineral belt (Tweto and Sims, 1963) and may have been part of a regional wrench-fault system called the Colorado lineament (Warner, 1978). In the Front Range a set of northwest- and north-northeast-trending fault zones is younger than the shear zones, but also formed in Precambrian time. Many of these fault zones were reactivated during Phanerozoic deformations (Tweto and Sims, 1963).

OIC, TRIASSIC, AND JURASSIC ROCKS

Paleozoic rocks ranging from Cambrian through Mississippian comprise a shelf sequence that was deposited across all of central Colorado. In the field trip area they range from 200 m thick on the east flank of the Sawatch Range to 400 m on the White River Uplift. These strata were eroded from the major late Paleozoic uplifts and are preserved only in the intervening late Paleozoic basins (figure 4). Older Paleozoic rocks are missing along the eastern flank of the Front Range north of Colorado Springs and in North Park, Middle Park, and eastern South Park. They are preserved in the Mosquito and Sawatch Ranges, where they host ore deposits at Leadville, Gilman, and Aspen, and to the west in the Eagle Basin.

Major elongate uplifts, commonly referred to as the Ancestral Rocky Mountains, began to form in Early or Middle Pennsylvanian time. As the uplifts rose, older Paleozoic strata were stripped, exposing Precambrian rocks over broad areas of the uplift. Clastic sedimentary rocks of Pennsylvanian and Permian age shed from the uplifts accumulated in the flanking basins, locally attaining thicknesses of more than 5 km. The sediments become finer grained towards the interior of the basins, and locally thick sections of evaporites were deposited in sub-basins, which were at least in part controlled by intrabasin deformation (DeVoto and others, 1986). The principal late Paleozoic uplifts in central Colorado were the Front Range Highland, which occupied much of the area of the present Front Range, and the Uncompahgre Highland that lay southwest and west of the present Sawatch Range and extended southeastward to the present San Luis Valley. Between the two uplifts was the Central Colorado Trough, the northwestern part of which comprises the Eagle Basin (Figure 3).

Thick clastic sequences derived from the late Paleozoic uplifts are overlain by Permian, Triassic, and Jurassic fluvial, eolian, and shoreline deposits that record gradual erosion and submergence of the Ancestral Rocky Mountain uplifts.

General variation in thickness of these sequences along the route of the field trip is illustrated in Figure 4; the units are listed and briefly described in Table 1.

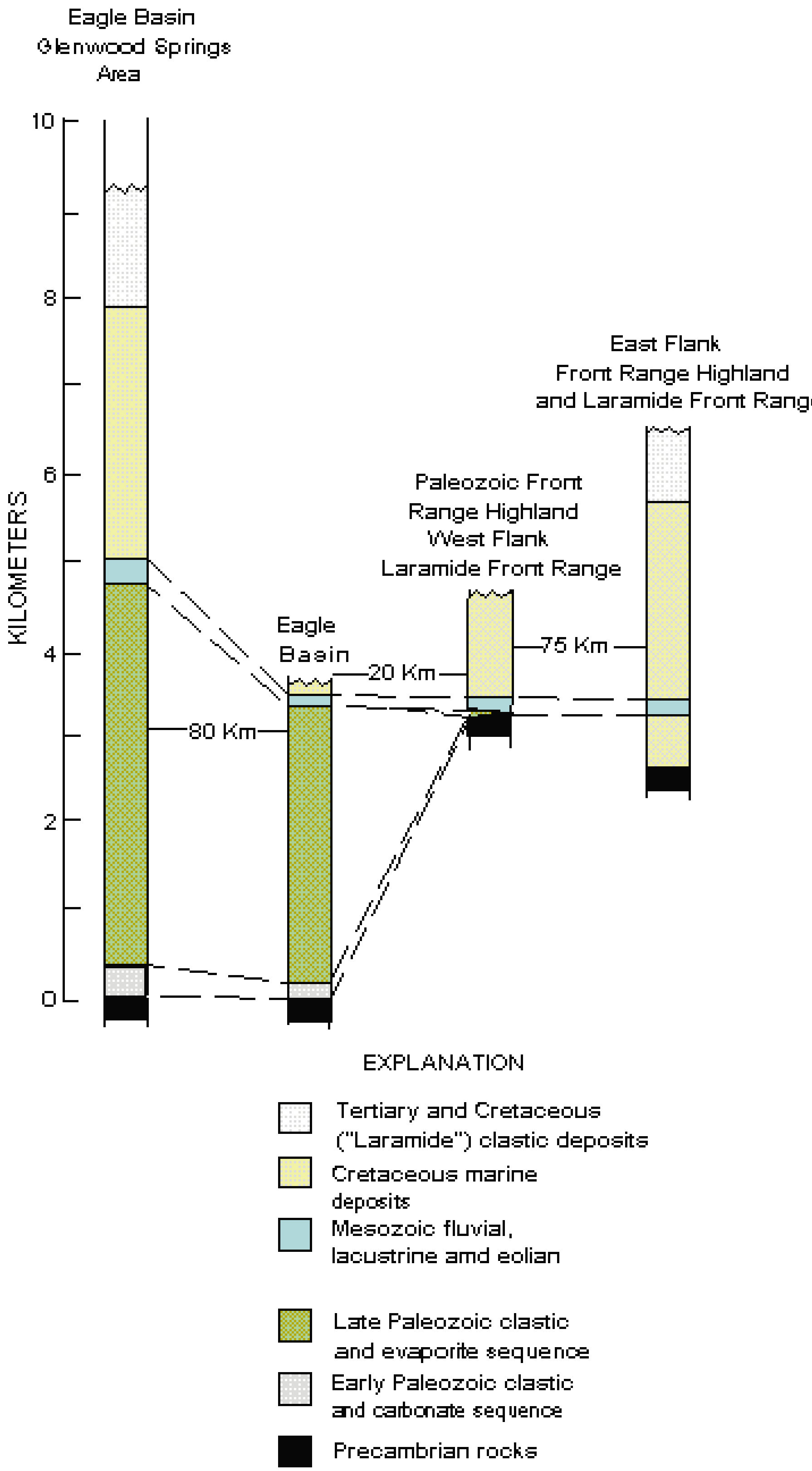


Figure 4. Comparison of generalized stratigraphic sections from the Denver basin across the Front Range Highland and into the Eagle basin along the field trip route. Sections correspond to those in Table 1.

Table 1. Generalized stratigraphic sections in central Colorado.

	Thickness (meters)
East Flank of Front Range in Morrison quadrangle (Scott, 1972)	
Green Mountain Conglomerate (Paleocene)	
Conglomerate, sandstone, and shale. Contains andesite pebbles.	200
Denver Formation (Paleocene and Upper Cretaceous)	
Brown to olive gray claystone, siltstone, sandstone, and conglomerate. Rich in andesite pebbles.	290
Arapahoe Formation (Upper Cretaceous)	
White, gray, and yellow sandstone, siltstone, claystone, and conglomerate. Conglomerate clasts are Phanerozoic sedimentary rock and Precambrian igneous and metamorphic rock.	120
Laramie Formation (Upper Cretaceous)	
Gray siltstone and claystone and yellow and white sandstone. Coal in lower part.	165
Fox Hills Sandstone (Upper Cretaceous)	
Olive to brown silty shale and yellowish-orange sandstone.	55
Pierre Shale (Upper Cretaceous)	
Olive-green shale, some beds of olive to gray sandstone, and limestone concretions.	1890
Niobrara Formation (Upper Cretaceous)	
Smoky Hill Shale Member:	
Pale to yellowish-brown, thin-bedded calcareous shale and thin-bedded limestone.	125
Fort Hays Limestone Member: Yellowish-gray dense limestone.	10
Carlile Shale, Greenhorn Limestone, and Graneros Shale (Upper Cretaceous).	160
Dakota Group (Lower Cretaceous)	
Yellowish-gray sandstone and dark gray shale; yellowish-brown sandstone and conglomerate at base. Divided into the South Platte (upper) and Lytle (lower) Formations.	90
Morrison Formation (Upper Jurassic)	
Red and green siltstone and claystone. Minor beds of brown sandstone and gray limestone.	90
Ralston Creek Formation (Jurassic)	
Purplish-gray sandstone and siltstone, yellow silty sandstone.	27
Lykins Formation (Triassic? and Permian)	
Maroon shale, sandy limestone, and maroon and green siltstone.	60
Fountain Formation (Permian and Pennsylvanian)	
Maroon arkosic sandstone and conglomerate.	500
Precambrian rocks.	
Paleozoic Front Range Highland and West Margin of Laramide Front Range Uplift in Blue River Valley near Dillon (Robinson, Warner, and Wahlstrom, 1974)	
Pierre Shale (Upper Cretaceous)	
Dark-gray to black shale.	760±
Niobrara Formation (Upper Cretaceous)	
Smoky Hill Marl Member: Dark gray, calcareous shale and thin-bedded limestone.	140
Fort Hays Limestone Member: Gray, dense, medium-bedded limestone with partings of calcareous shale.	4–6
Benton Shale (Upper Cretaceous)	
Dark-gray to black shale.	60±
Dakota Sandstone (Lower Cretaceous)	
Gray sandstone and gray to black shale.	55±

Table 1. Continued.

Morrison Formation (Upper Jurassic)
    Gray and greenish-gray claystone; local sandstone and limestone. . . . . .180±
Entrada? Sandstone (Middle Jurassic)
    Gray cross-bedded sandstone. 0–45
Lykins Formation (Triassic? and Permian)
    Red and variegated siltstone and sandstone. . . . . .60±
Maroon Formation (Permian and Pennsylvanian)
    Red, pink, and gray arkosic sandstone and conglomerate. . . . . .30±
Precambrian rocks

Northeast Flank of Eagle Basin in Minturn quadrangle (Tweto, 1977)

Dakota Sandstone (Upper Cretaceous)
    Medium bedded to massive gray sandstone. 45–49
Morrison Formation (Upper Jurassic)
    Gray sandstone, green, gray, and purple shale; gray limestone. .76
Entrada Sandstone (Middle Jurassic)
    Massive, cross bedded, buff to orange sandstone. 18
Chinle Formation (Upper Triassic)
    Red and purple siltstone, mudstone, and sandstone. 21
Maroon Formation (Lower Permian, Upper and Middle Pennsylvanian)
    Red sandstone, siltstone, grit, and conglomerate. 520–1280
Minturn Formation (Middle Pennsylvanian)
    Grit, conglomerate, sandstone, and shale, and some intercalated limestone
    and dolomite. Predominantly gray, but red in upper part and near base. 600–1,900
Belden Formation (Middle Pennsylvanian)
    Gray to black shale, limestone, and minor sandstone. 0–60
Molas Formation (Lower Pennsylvanian)
    Green, yellow, or brown regolithic clay. 0–3
Leadville Limestone (or Dolomite) (Lower Mississippian)
    Gray limestone or dolomite. 0–45
Chaffee Group (Lower Mississippian? and Lower Devonian)
    Gilman Sandstone: Yellowish-gray sandstone, sandy and cherty dolomite,
    and breccia. 3–15
Dyer Dolomite: Thin-bedded gray dolomite. 0–25
Parting Formation: White to tan sandstone and conglomerate with subordinate
    green shale. 0–20
Harding Sandstone (Middle Ordovician)
    White, gray, and green sandstone and green shale. . . . . .0–25?
Peerless Formation (Upper Cambrian)
    Brown, red, green, and buff sandy dolomite and dolomitic shale. 0–21
Sawatch Quartzite (Cambrian)
    Medium-grained white quartzite. 0–67
Precambrian rocks.

White River Uplift and Southeastern Piceance Basin (Bass and Northrop, 1963; Johnson and others, 1990; Kirkham and others, 1995a, b)

Conglomerate of Canyon Creek (Miocene?)
    Cobble conglomerate and a few local sandstone beds. . . . . .max. 360

Table 1. Continued.

Basalt (Miocene)
Basalt, olivine basalt, and andesitic basalt flows and pyroclastics, and interbedded siltstone, conglomerate, sandstone, and claystone. . . . . .max. 75
Wasatch Formation (Paleocene and Eocene)
Reddish-brown, reddish-purple, yellowish-brown, tan, and white sandstone, siltstone, conglomeratic sandstone, conglomerate, mudstone, and claystone. 1525
Mesaverde Group (Upper Cretaceous)
Yellowish-gray fine-grained sandstone, yellowish-brown and olive-gray carbonaceous mudstone and shale, and coal. 1430
Mancos Shale (Upper Cretaceous)
Light to dark gray, locally bentonitic, carbonaceous shale. 1280
Niobrara Formation (Upper Cretaceous)
Gray, white-weathering, calcareous shale and shaley limestone; limestone beds in lower part. 100
Frontier and Mowry Formations (Upper Cretaceous)
Dark gray shale (20 m), calcareous sandstone and sandy shale (15 m), dark gray shale (35 m), and siliceous shale and gray shale containing fish scales (15 m). 85
Dakota Sandstone (Lower Cretaceous)
Yellowish-brown, medium- to coarse-grained, massive to cross-bedded sandstone containing lenses of chert-pebble conglomerate and beds of dark gray to black carbonaceous sandy siltstone and mudstone. 28–53
Morrison Formation (Upper Jurassic)
Medium to light green and grayish-red mudstone and shale and dark gray limestone; beds of silty sandstone near base. 120–150
Entrada Sandstone (Middle Jurassic)
Light gray to light orange, medium- to very fine-grained, cross bedded sandstone. 15–30
Chinle Formation (Upper Triassic)
Dark reddish-brown, orangish-red, and purplish-red calcareous siltstone, light purplish-red and gray limestone and limestone pebble conglomerate. Sandstone of the Gartra Member locally present at base. 68
State Bridge Formation (Lower Triassic? and Permian)
Pale red, grayish-red, reddish-brown, and greenish-gray siltstone, clayey siltstone and minor sandstone. Light gray South Canyon Creek dolomite Member 1-2 m thick divides the formation into upper and lower members. 48
Maroon Formation (Permian and Pennsylvanian)
Includes Schoolhouse Member at top, a gray fine- to coarse-grained sandstone that is locally dark gray where it contains dead oil. Grayish-red, pale red, and reddish-brown arkosic sandstone, conglomerate, siltstone, and mudstone, and a few thin beds of gray limestone. 900–1500
Eagle Valley Formation (Middle Pennsylvanian)
Reddish-brown, gray, reddish-gray, and tan siltstone, shale, sandstone, gypsum, limestone, and dolomite. 150–300
Eagle Valley Evaporite (Middle Pennsylvanian)
Gypsum, anhydrite, halite, and gray partly gypsiferous siltstone and shale, sandstone, limestone, and dolomite. 365–2700
Belden Formation (Lower Pennsylvanian)
Medium gray to black and dark brown calcareous shale and gray fossiliferous limestone. 200–250
Leadville Limestone (Mississippian)
Gray to bluish-gray, coarse- to fine-grained limestone and dolomite. 60

Table 1. Continued.

Chaffee Group (Upper Devonian)	
Gilman Sandstone: Tan to yellow fine-grained dolomitic sandstone.	0–5
Dyer Dolomite:	
Coffee Pot Member: Micritic dolomite, dolomitic shale, and limestone.	30
Broken Rib Member: Gray, nodular, fossiliferous limestone.	20
Parting Formation: White to buff quartzite, green shale, and gray dolomite.	20–30
Manitou Formation (Lower Ordovician)	
Tie Gulch Dolomite Member: Brown and orange-weathering micritic, somewhat siliceous, dolomite.	20
Dead Horse conglomerate Member: Flat-pebble limestone conglomerate, thin-bedded limestone, shaly limestone, and dolomitic quartzite.	30
Dotsero Formation (Upper Cambrian)	
Clinetop Member: Stromatolitic limestone and limestone pebble conglomerate.	1–2
Glenwood Canyon Member: Thinly bedded dolomite, dolomitic sandstone, conglomeratic limestone,limestone, and dolomitic shale.	30
Sawatch Quartzite (Upper Cambrian)	
White and buff to gray-orange, brown-weathering vitreous quartzite. Beds of massive brown sandy dolomite in upper part. Local arkosic quartz-pebble conglomerate at base.	165
Precambrian rocks	

CRETACEOUS AND CENOZOIC ROCKS

A blanket of intertonguing marine and continental rocks of Cretaceous age, locally nearly 3 km thick, was deposited across the entire Southern Rocky Mountain region, covering the eroded roots of the late Paleozoic uplifts and the intervening basins. Cretaceous rocks were largely derived from sources to the west and record several cycles of westward marine transgression and eastward regression. The beginning of the Laramide orogeny is recorded in structural basins throughout the region by the abrupt transition from fine-grained Upper Cretaceous rocks of far western derivation to orogenic sediments from local sources. In the Denver basin this change is marked by the transition during the Maastrichtian from the marine Fox Hills Sandstone to nonmarine, coal-bearing strata of the Laramie Formation and sandstone and conglomerate of the Arapahoe Formation. In South Park west of the Front Range Uplift, the Laramie is unconformably overlain by volcanic detritus in the basal part of the South Park Formation, which is earliest Paleocene or latest Cretaceous in age.

The onset of Laramide deformation was accompanied by the inception of igneous activity. Calc-alkalic magmas formed intrusions and volcanic fields that are especially numerous in the Colorado lineament. Ore deposits associated with this igneous activity, which continued intermittently until the end of Oligocene time, were a major factor that led to the settlement of Colorado.

In the Piceance Basin southwest of the White River Uplift, late Campanian or early Maastrichtian beds of the Mesaverde Group were eroded and deeply weathered before being overlain by late Paleocene mudstone, sandstone, and conglomerate of the late Paleocene and Eocene Wasatch Formation (Johnson and May, 1980).

Conglomerates in the Wasatch Formation are most numerous and coarser grained near the base of the formation along the east margin of the basin south of Glenwood Springs. They are rich in clasts of volcanic and hypabyssal rock, suggesting that the Sawatch uplift was a major source of the detritus. By middle Eocene time the Green River Formation was being deposited in Lake Uinta, which occupied much of the Piceance Basin. Sandstones in the Green River Formation are coarser along the margin of the basin suggesting initial doming of the White River Uplift. The Green River Formation and overlying Uinta Formation are deformed along the west margin of the White River Uplift indicating that the uplift did not attain its present shape and structural relief until middle Eocene time or later.

By late Eocene time a widespread erosional surface had developed in Colorado (Scott, 1975). This surface is commonly preserved where overlain by late Eocene volcanic rocks, such as in South Park and the San Juan Mountains. Late Eocene and Oligocene were times of widespread igneous activity now manifested by the volcanic rocks and calderas of the San Juan Mountains, South Park, and Sawatch Range, and by intrusions in the Elk Mountains and Sawatch Range. Early Miocene basalts flowed out onto an erosion surface that had beveled the top of the White River Uplift and rocks as young as middle Eocene in the Piceance Basin to the west. Whether this surface persisted from late Eocene time or is a younger surface is not proven in the area of the field trip, but to the south in the San Juan Mountains, early Miocene basalts cover an erosional surface cutting Oligocene volcanic rocks (Steven and others, 1995). Basalt and rhyolite flows and tuffs and granite plugs were emplaced while extensional deformation displaced the old surfaces and produced new basins, most notably on the trend of the Rio Grande Rift. Much of the present topographic relief is the result of differential uplift, collapse, and dissection during the Neogene. The importance of post-Laramide uplift, at least locally, if not regionally, in shaping the present mountain landscape is illustrated by the fact that of 54 peaks in Colorado over 4,267 m (14,000 feet) high, all but two lie either along the crest of the Alvarado ridge on the flanks of the Neogene Rio Grande Rift or along a low-density composite batholith of the Colorado mineral belt. Moreover, four of the five highest peaks lie near the intersection of these features.

Evidence of Neogene volcanism and tectonism is widespread in the Glenwood Springs area. Neogene volcanic rocks here range from 22.4 to 3.9 Ma (Larson and others, 1975; Kirkham and others, 1995a, b) and are useful for interpreting the geomorphic development of the Colorado River system. The oldest Quaternary basaltic volcanism (1.3-2.0 Ma; Larson and others, 1975) occurred in the Roaring Fork Valley about 45 km southeast of Glenwood Springs, whereas the youngest known volcanic rocks in Colorado (4.15 ka; Giegengack, 1962) are near Dotsero. Spectacular Glenwood Canyon was carved by the Colorado River during the Neogene, perhaps even late Neogene. Faulted Neogene basalts and surficial deposits along the Grand Hogback Monocline suggest significant post-Laramide bedding-plane slippage. Diapirism and flowage of evaporitic rocks caused faulting in overlying basalts, upwarping along the Roaring Fork and Eagle Rivers, and probably caused the subsidence which formed Spring Valley. Remnants of formerly extensive debris-flow deposits near New Castle and well preserved terraces along the Roaring Fork River record erosional and depositional events during the Quaternary.

A variety of geologic hazards affect the Glenwood Springs area, including debris flows and hyperconcentrated flows, landslides and rockfall, sinkholes, low-strength, hydrocompactive, and corrosive surficial deposits, and perhaps earthquakes.

ROAD LOG

Day One

Downtown Denver is built upon alluvial and eolian deposits that overlie Upper Cretaceous-Paleocene volcaniclastic conglomerate to claystone of the Denver Formation. From downtown Denver to the mountain front the route crosses a small part of the east flank, axis, and west flank of the asymmetric Denver Basin. After crossing the South Platte River, the route ascends to a surface underlain by Verdos Alluvium, which locally contains ash correlated with the 0.62 Ma Lava Creek B ash bed (Madole, 1991).
Roadlog mileage starts at the interchange of US Highway 6 (West 6th Avenue) and Union Street at the northwest corner of the Denver Federal Center, near where the route climbs up onto the hills underlain by the Denver Formation. Note that road log mileage is in miles, whereas metric units are used in the text.

Mileage (in miles)

0.0 Interchange of US Highway 6 and Union Street is near the deepest part of the Denver Basin, where basement rocks are 3.5 km below the surface. In the Mount Evans area of the Front Range, apatites were annealed in Laramide time up to an altitude of 3,500 m. Calculated structural relief between the Front Range near Mt. Evans and the deepest part of the Denver Basin is about 6.5 km (Bryant and Naeser, 1981).

1.7 Table Mountain at right capped by potassic basalt (shoshonite) lava flows about 65-64 Ma (Scott, 1972). Cretaceous-Tertiary boundary is below the cap and exposed at the east end of the mesa. Green Mountain on left is composed of Paleocene sandstone, conglomerate, and shale.

2.7 Leave Highway 6 and head west-bound on Interstate Highway 70 (I-70). On west side of Green Mountain and west of Table Mountain, dips increase abruptly. Just east of Dakota Hogback about 1,600 m of Upper Cretaceous rocks are cut out by the Golden Fault, the principal flank structure on the east side of the Front Range Uplift in this area.

4.2 White sandstone on left beneath surficial deposits is the Fox Hills, a regressive shoreline deposit that predates the Laramide orogeny.

4.7 Excellent exposures of Dakota Group and underlying Jurassic Morrison and Ralston Creek Formations in hogback roadcut.

5.0 Small exposure of Permian Lyons Sandstone on right. Fountain Formation, which forms spectacular exposures in Red Rocks Park 3.2 km to the south, is mostly cut out by a fault that trends northeast from Proterozoic rocks in Cherry Gulch 0.8 km south of here and then north along the margin of the Proterozoic crystalline rocks.

5.3 Entering Mount Vernon Canyon. Rocks at mouth of canyon were fractured by the Cherry Gulch Fault. Excellent exposures of interlayered felsic gneiss, hornblende gneiss, and amphibolite, typical of rocks mapped as “felsic and hornblendic gneisses” on the state geologic map (Tweto, 1979), can be seen in this canyon. Gneisses have abundant evidence of intense layer parallel ductile deformation, as well as intrafolial isoclines on scales of a few centimeters to tens of meters that are locally conspicuous. A variety of open folds and warps are superimposed on the isocline limbs. Layered gneisses are cut by discordant to semi-concordant dikes and pods of pink granite. Some dikes are folded or boudinaged, and some are cut by veins of white quartz that fill gash fractures. Gneisses are likely of volcanic origin.

7.6 For the next 3 km (1.9 miles) exposures are rare as we approach gentler topography interpreted as the dissected late Eocene erosion surface, although its age is not well constrained.

9.6 Crossing rolling topography of the erosion surface for next 11 km (6.9 miles). Remnants of this surface north of Clear Creek Canyon are visible from several points. Also visible are ridges capped by Miocene or Pliocene boulder gravel that occupies an ancestral channel of Clear Creek incised several hundred feet into the erosion surface and which lies 120 to 180 m above the present stream. Remnants of the gravel can be traced discontinuously to near the canyon mouth, where they lie a couple of hundred meters above the projection of the surface formed by one of the oldest Quaternary alluvial deposits, the Rocky Flats Alluvium.

16.6 Overpass at top of Floyd Hill. Cross Floyd Hill Fault Zone, one of a series of northwest-trending fault zones in this part of the Front Range. Apparent left-lateral offset of Proterozoic units is as much as 610 m. Neogene dip-slip of nearly 610 m with northeast side down has been inferred from offset of the late Eocene erosion surface (Scott, 1975), although Dickson and others (1986) dispute this evidence.

17.6 Ridge north of Clear Creek is capped by Miocene or Pliocene boulder gravel filling a channel of ancestral Clear Creek. Roadcuts on grade down Floyd Hill are in interlayered felsic gneiss, hornblende gneiss, and amphibolite cut by dikes of pink granite and pegmatite.

19.7 Large roadcuts on right just after crossing Clear Creek expose migmatitic biotite gneiss and schist, cut by dikes of pink granite and pegmatite. These are typical of rocks mapped as biotite schist, gneiss, and migmatite on the state geologic map (Tweto, 1979).

21.7 At east portal of highway tunnel are spectacular outcrops of felsic gneiss and amphibolite. Felsic gneiss is fine- to medium-grained light gray, tan, or pink and contains subequal amounts of quartz and oligoclase, 5 to 40 percent microcline, and 5 percent or less biotite. Previous workers in the Idaho Springs area mapped three major layers of felsic gneiss 100-1000 m thick interleaved with migmatitic biotite gneiss. They interpreted the felsic gneiss as a metasedimentary rock and treated the stack of layers as a stratigraphic sequence. These outcrops are in the Idaho Springs layer, which they regarded as the lowest felsic gneiss layer. The chemistry of the felsic gneiss suggests that it is more likely of igneous (possibly volcanic) origin, and abundant intrafolial isoclines and other evidence of layer-parallel ductile deformation indicate that the sequence is more likely tectonic.

22.7 Enter Colorado Mineral Belt and Central City-Idaho Springs mining district. District straddles the Idaho Springs-Ralston shear zone, one of the northeast-trending zones of cataclastic and ductile deformation in the Front Range (Tweto and Sims, 1963). Small plutons of calc-alkalic and alkalic rock are numerous in the mining district. Ore deposits are sulfide-quartz veins that contain gold, silver, copper, lead, and zinc. District is zoned with a large area of gold-bearing pyrite-quartz veins in the interior, an intermediate zone of pyrite-quartz veins bearing copper, lead and zinc, minerals, and a peripheral one containing galena-sphalerite-quartz-carbonate veins (Simms, 1989).

23.2 Dump from Argo tunnel on right. Tunnel was driven 6 km northward to intersect veins of the Central City area at depth, dewater existing mines, and provide easy transportation of ore to mills at Idaho Springs. Tunnel was completed in 1910 and operated intermittently until 1943 when a drill hole penetrated water-filled stopes of an inactive mine, triggering a flood in which four men drowned. Tunnel has not been reopened.

24.7 On right just west of western Idaho Springs exit (#239) fractured and iron-oxide stained felsic gneiss crops out in Idaho Springs-Ralston Shear Zone. For the next 11 km (7 miles) exposures are chiefly interlayered felsic gneiss, biotite gneiss, and amphibolite, cut by bodies of gneissic granite of the Routt Plutonic Suite and by dikes of Silver Plume Granite and related pegmatite. Outwash gravels locally form prominent terraces along Clear Creek.

25.7 Enter Lawson-Dumont-Fall River mining district, a part of the Idaho Springs-Central City mineralized area, which the route follows for the next 10 km (6.3 miles). Silver, lead, zinc, and gold were produced from narrow fissure veins along minor faults (Hawley and Moore, 1967).

31.7 Just beyond junction with U.S. 40 is the poorly defined terminal moraine of the late Pleistocene Clear Creek valley glacier. Terminal moraine of the West Fork of Clear Creek is visible a few hundred meters to west. Valley from here to Georgetown is chiefly in biotite gneiss cut by myriad dikes and irregular intrusive bodies of Silver Plume Granite. Landslides are conspicuous in several places, particularly on east side of valley above the reservoir near Georgetown.

36.4 Georgetown exit (#228). Entering Georgetown-Silver Plume mining district. High roadcuts along north side of I-70 along steep grade above Georgetown are layered biotite gneiss and amphibolite cut by a network of dikes of Silver Plume Granite and pegmatite. These cliffs pose one of the worst highway rockfall hazards in the state (R. Andrew, 1996, oral commun.). This mining district produced silver, lead, zinc, and minor gold from veins cutting Early Proterozoic schist and gneiss and Middle Proterozoic granite. Main productive veins trend northeastward and west-northwestward parallel to major Precambrian fault zones. Dikes of leucocratic rhyolite-granite B porphyry 37 to 40 Ma are closely associated with the veins, which are interpreted as distal epithermal, magmatic hydrothermal veins related to a large probably composite granite B batholith at depth (Brookstom, 1988).

39.7 Quarry at west outskirts of Silver Plume is type locality of Silver Plume Granite, one of the Middle Proterozoic peraluminous granites that occur over a broad area on the North American craton (Anderson, 1983). Zircon from the granite has been dated by U-Pb isotopic methods at 1,422±2 Ma (Graubard and Mattison, 1990). This is the most widely known of the 1.4 Ga granites in Colorado, which Tweto called the Berthoud Plutonic Suite. Geochemical study of Silver Plume batholith indicates that it was derived from relatively dry, peraluminous, oxidized lower crust and emplaced in upper crust at depths of 9.7 to 11.2 km or shallower and at temperatures of 740–760°C at an elevated fO_2 (Anderson and Thomas, 1985).

40.0 Cross Browns Gulch, site of a “suburb” of Silver Plume called Brownsville. Several disastrous debris flows composed of mine dump and colluvial material swept into the settlement. In 1912 a large flow wiped out structures remaining in Brownsville. Valley above here is largely in biotite gneiss cut by many intrusive bodies of Silver Plume, but exposures are poor at road level. Several conspicuous avalanche tracks scar valley walls.

43.1 Brief glimpse of Torreys Peak (4,348 m) on left at Bakerville exit (#221). Torreys and its neighbor

Grays Peak (4,349 m) are the highest peaks in the Front Range and are the only "fourteeners" (4,267 m) in Colorado whose summits lie on the continental divide.

45.1 About 3.2 km (2 miles) west of Bakersville enter a wide belt of fractured and sheared rocks along the north-northeast-trending Loveland Pass-Berthoud Pass fault zone. Outcrop is spotty in the lower valley despite being in the interior of the Silver Plume batholith. Mount Bethel (symmetrical peak north of road) is largely fractured Silver Plume. Snow fences on ridge and diversion structures at mouth of prominent chute aid avalanche control efforts on I-70.

49.4 Loveland ski area and Seven Sisters avalanche chutes on left. Enter east portal of Eisenhower Tunnel, one of the highest highway tunnels in the world, which carries I-70 under the continental divide. It passes through fractured and sheared biotite gneiss and Silver Plume Granite in the Loveland Pass-Berthoud Pass fault zone. The broken rock and large diameter necessary to provide ventilation at 3,400 m altitude led to delays and major cost-overruns during construction of the first bore.

51.1 Outcrops north of the west portal of the Eisenhower Tunnel are near western contact of Silver Plume Batholith. Valley of Straight Creek, along which the highway descends, is controlled by a zone of faults that branches southwest off the Loveland Pass-Berthoud Pass Fault Zone. Rocks in roadcuts are chiefly biotite gneiss. Active landsliding in till and along south-dipping foliation planes in gneiss disrupted construction of highway and necessitated its re-alignment (Robinson and others, 1976). View of Blue River Valley and Gore Range ahead, which are Neogene structures related to the Rio Grande Rift.

57.4 Cross Williams Range Thrust near bottom of grade, passing from broken Precambrian rocks in the upper plate into Upper Cretaceous Pierre Shale in lower plate. This north-northeast-dipping, low-angle thrust forms the west margin of the Laramide Front Range Uplift. It is much longer and more continuous than the Golden Fault, and map relations show a minimum of 8 km of westward displacement of the upper plate just south of here. About 1.6 km west of the main thrust a minor thrust fault is exposed in Dakota Sandstone in a large roadcut on the right.

59.1 Dillon/Silverthorne exit (#205). Gore Range and Blue River to right; Dillon Dam on left. Denver Water Department transports water from Dillon Reservoir to Denver via the 38-km-long Roberts Tunnel. The Blue River Valley, which follows a north-northwest-striking belt of sedimentary rock west of the Front Range Uplift, is a Neogene half-graben en echelon with the Upper Arkansas Valley Graben. There has been at least a kilometer of Neogene uplift along the Blue River Fault on west side of the half-graben. To north downthrown side of half-graben is mostly concealed by glacial deposits, but a few exposures suggest the presence of numerous fault blocks of other Miocene sediments and Oligocene volcanic rocks. This part of the Gore Range is composed of migmatite and granitic rocks of the Routt Plutonic Suite.

59.4 Yellowish gravel exposed across the small valley on right about 1.6 km after crossing the Blue River is probably equivalent to the Pliocene-Miocene Dry Union Formation in Upper Arkansas Valley.

61.5 Views west and south across Dillon Reservoir towards west flank of Front Range and east side of Tenmile Range. Precambrian rocks are thrust over Cretaceous shale along the slope above the highest breaks in the forest. To south Mt. Guyot (on left; 3,983 m) and Bald Mountain (on right; 4,146 m) are formed by late Eocene intrusions in Mesozoic sedimentary rocks west of the Front Range Uplift and separate Middle Park from South Park. Rocky slopes to south are north end of Tenmile Range, which is part of the same tectonic block as the Gore Range. West side of valley is bounded by Blue River Fault, a major tectonic element of the Neogene rift system at this latitude. This area is on the west margin of the late Paleozoic Front Range Highland. Upper Jurassic rocks lie on Precambrian basement to the southeast; at Dillon dam 30 m of redbeds of possible late Paleozoic age separate Jurassic rocks from the basement. Low hills near reservoir are late Pleistocene moraines.

62.0 Frisco exit (#201). Enter canyon of Tenmile Creek, which forms physiographic boundary between Tenmile Range to the east and Gore Range to the west. Structural boundary between the ranges is formed by the Mosquito Fault Zone about 1 km to the west. In Tenmile Canyon Precambrian rocks consist of layered hornblende and biotite gneiss and amphibolite cut by light colored anastomosing pegmatite dikes. Most gneisses are probably metamorphosed volcanic and volcaniclastic rocks similar to those preserved in less metamorphosed and deformed sequences near Salida and Gunnison. Rocks here locally contain small amounts of orthopyroxene coexisting with hornblende and calcic plagioclase suggesting metamorphic grade close to the amphibolite-granulite facies transition. Other exposed rocks are migmatitic biotite gneiss and quartz-feldspar gneiss (Reed, 1988).

67.2 Scenic turnout lies nearly on the Mosquito Fault; mylonitic rocks crop out on both sides of valley. Southward the valley roughly parallels the fault, which separates Precambrian rocks like those exposed in canyon on the east from Pennsylvanian and Permian strata of Eagle Basin on the west. Exploration at Climax molybdenum mine 24 km south found that the fault dips 70° west and has a vertical displacement of 2,700 m and left lateral displacement of 450 m, which occurred after late Oligocene time.

72.2 Jacque Peak to left, with east-dipping strata on skyline to west. Kokomo mining district is 3.2 km south. Well below the skyline is base of Permian/Pennsylvanian Maroon Formation marked by Jacque Mountain Limestone Member of the Middle Pennsylvanian Minturn Formation (Table 1). Numerous Tertiary sills intrude these sediments. Exposures of red sandstone and conglomerate to right are in downdropped block along the Gore Fault, which we crossed in an area covered by surficial deposits.

73.3 Vail Pass rest area (#190).

73.7 **STOP 1. View of Gore Fault at margin of Eagle Basin.** Pull off of I-70 at the parking area. Uphill to the east the Gore Fault lies about at slope break. To north it is left of the peaks above timberline. Above us the attitude of the fault is not known but to the north it dips northeast as little as 45°. Gently south-dipping beds of Minturn Formation west of fault are abruptly pushed into vertical to steeply overturned dips next to fault. Prominent resistant beds are carbonate beds of the Robinson Limestone Member. The Gore Fault moved as early as Precambrian time. It was inactive during Middle Pennsylvanian when rocks now adjacent to it were deposited, but later in Pennsylvanian or Early Permian time it formed the west margin of the Front Range Highland. Minturn Formation and older rocks are missing and Maroon Formation is only 100 m thick on crest of Gore Range east of the Gore Fault and north of the high peaks, the most uplifted part of the range. No evidence for Laramide activity on the Gore Fault is known, although Tweto and Lovering (1977) state that regional relations require that it was active then. Significant Neogene displacement along the Gore Fault is indicated by apatite fission-track studies in progress by C.W. Naeser. Continue westbound on I-70.

74.3 Over next 13 km (8.1 miles) highway descends into the valley of Gore Creek through Pennsylvanian redbeds of Minturn Formation. When these sediments were deposited the Gore Fault was not the margin of the basin, because sparse intercalated marine limestone beds extend right up to the fault. However, thickness of Minturn Formation decreases towards the fault, suggesting the margin of the Front Range Highland at that time was farther east.

82.3 Cross Gore Creek. Enter resort complex of Vail. Route follows I-70 through Vail valley for the next 3.2 km (2 miles). Note hazardous avalanche chutes and runout zones in upper end of valley. Vail now is zoned for geologic hazards.

84.8 Rockfall from cliff on right damaged structures in 1983, 1986, and 1987 (Stover, 1988). A debris flow from the next major valley on the right, Booth Creek, damaged several houses in the mid-1980s.

91.4 Large roadcuts in sandstone, limestone, dolomite, and conglomerate of Minturn Formation. Detailed sedimentological study reveals a number of cycles that represent shallow marine to alluvial-fan deposition (Johnson and others, 1988).

92.1 Cross Eagle River. Minturn/Leadville exit (#171). Debris from landslide on left blocked eastbound lane of I-70 several times during wet periods in 1983, 1984, and 1985. I-70 curves left around the toe of Whiskey Creek landslide, which extends more than 600 m vertically up the valley wall. Any major activity on it would endanger the highway and railroad and might dam the Eagle River (Soule, 1988).

93.1 Massive, resistant, coarse-grained clastics in Minturn Formation abruptly change facies into gypsiferous siltstone and mudstone of Middle Pennsylvanian Eagle Valley Evaporite; type section is north of I-70 about 2 km (1.3 miles) before Avon (Lovering and Mallory, 1962).

96.1 Avon exit (#167). West-facing, light-colored, steep-walled bluff on left across Eagle River is an outcrop of fairly pure gypsum in the Eagle Valley Evaporite.

98.7 Edwards exit (#163).

100.1 West of Edwards there are good views of the northern part of the Sawatch Range to the left. Peak on right is New York Mountain, with a dip slope of Cambrian Sawatch Quartzite on ridge to right. Jagged peaks are largely biotite gneiss and migmatite.

101.1 Wilmor Lake rest area (#162). Near vertical beds in roadcut are within the east flank of Wolcott syncline. These beds are probably equivalent to the Eagle Valley Formation, a sequence of rocks mapped by Tweto (1978) and Kirkham and others (1995a, b) in the Glenwood Springs area in which the Eagle Valley Evaporite grades into and intertongues with basal Maroon Formation. Dakota Sandstone forms skyline to west and is underlain by Morrison, Entrada, Chinle, State Bridge, and Maroon Formations. Mesozoic rocks exposed in Wolcott Syncline for next 12 km. Jurassic Entrada Sandstone forms prominent ledge at top of the redbeds and is overlain by nonresistant light gray and greenish-gray Jurassic Morrison Formation, ledge-forming Lower Cretaceous Dakota Sandstone, black Upper and Lower Cretaceous Benton Shale, and light gray calcareous limestone and shale of Upper Cretaceous Niobrara Formation. Formation contacts in redbeds below the Entrada are difficult to identify. Triassic Chinle Formation is somewhat darker red and less resistant than underlying formations. Its base is marked by a thin, resistant, pebbly sandstone, the Gartra Member, which forms a conspicuous ledge on west flank of the syncline. Also on this flank there is a light gray sandstone bed in the redbed sequence known as the Schoolhouse Member (Johnson and others, 1990); it marks the top of the Maroon Formation. Triassic(?)/Permian State Bridge Formation separates Chinle and Maroon Formations.

104.2 Overturned beds on right are in east limb of Wolcott Syncline.

106.1 Wolcott exit (#157).

109.0 Roadcut on right capped by Gartra Member, with State Bridge exposed beneath. Note recently reactivated landslide across river to left.

109.1 From west of Wolcott Syncline to mouth of Glenwood Canyon route is in highly deformed evaporite, mudstone, siltstone, limestone, and dolomite of Eagle Valley Evaporite exposed in a diapiric anticline. Note numerous outcrops of ductilely deformed evaporite on north side of highway.

116.1 Eagle exit (#147). High wooded hill to south is Hardscrabble Mountain. It is capped by State Bridge Formation in a north-dipping slab that includes beds up to Mancos Shale and is surrounded by an almost enclosed diapiric contact with Eagle Valley Evaporite. Note voids within Eagle Valley Evaporite on right. High peaks of Sawatch Range visible in far distance to southeast.

117.8 **STOP 2. Briefly discuss sinkholes associated with the Eagle Valley Evaporite.** Park on right shoulder. **DO NOT LEAVE VEHICLES.** Two sinkholes at the foot of the irrigated field measure about 5 x 7 x 1.3 m deep and 12 x 8 x 2 m deep and are developed in alluvial fan or pediment deposits overlying Eagle Valley Evaporite. They developed during 1994 when irrigation water was applied for the first time in many years. Landowner stated that prior to 1994 a small, eroded sinkhole was located where the feature on the right now occurs, but it was only about 1/3 to 1/2 of its current size. Failure may have initiated by hydrocompaction, but was probably mainly a result of piping of surficial deposits into a void in the underlying Eagle Valley Evaporite. Void spaces are relatively common in the Eagle Valley Evaporite, ranging from narrow, tight joint-like features to huge caverns up to several meters wide and 20 m deep.

Evaporitic rocks have been complexly deformed by 1) dehydration as gypsum converts to anhydrite after burial, 2) tectonism, 3) flowage related to differential loading due to erosional downcutting of major rivers, 4) hydration as anhydrite reverts to gypsum as overlying loads are reduced by uplift and erosion, and 5) diapirism. Drill holes in the Eagle Basin document presence of up to a few hundred meters of halite in the subsurface.

Voids within the evaporitic rocks may reflect locations where lenses, stringers, blebs, and other bodies of ductilely deformed deposits of halite and gypsum have been dissolved. High concentrations of sodium and chloride in hot springs in the region suggest dissolution still continues. Numerous sinkholes have been observed by the authors during the course of their field work. A few sinkholes have formed over karst features in limestone, but most are developed over evaporitic rocks. Many sinkholes have formed in surficial deposits such as terrace gravels, fan deposits, colluvium, and loess, and one very large one is in basalt. Hydrocompaction is responsible for most of the shallow (1–3 m deep) sinkholes in rapidly deposited, low-density surficial deposits, but it alone cannot account for sinkholes in terrace gravels or those that are several meters or more deep. Saturation of surficial deposits and particularly ponding of surface water seem to be contributing factors as well. Hydrocompaction and human activities may lead to ponding, particularly where fill placed in drainages interrupts natural flow paths. As water in the vadose zone moves down through soil overlying a bedrock void, it may wash soil into the void, creating a sinkhole. Irrigation ditches frequently have been disrupted by sinkholes. Local residents report that in some instances irrigation water in ditches has disappeared into newly created sinkholes with no noticeable filling of the feature or apparent leakage on adjacent hillslopes. In another case water flowing into a sinkhole re-surfaced downslope, causing considerable erosion and road damage.

123.1 Gypsum exit (#140). Plant on left uses gypsum from a mine north of the highway to make wallboard. Between Gypsum and Dotsero deformed beds within Eagle Valley Evaporite comprise lower slopes on north valley wall and are overlain by Eagle Valley and Maroon Formations (see Table 1).

128.4 Cross Dotsero basalt flow.

128.8 Leave I-70 at Dotsero exit (#133). Turn left at stop sign onto old US 6 & 24.

129.0 **STOP 3. Examine Dotsero basalt flow.** Park at locked gate on west edge of basalt flow. Private land beyond fence. Dotsero basalt flow issued from a steep-sided explosion crater (“The Blowout”) located about 1.5 km north of I-70, then flowed down a tributary drainage and onto the floodplain of the Eagle River. Crater is a closed depression 500 m wide by 750 m long by 98 m deep. Flow forms fan-shaped lobe of “aa” lava that extends to the

Colorado River. River was pushed against south valley wall by the flow, but there is no evidence to indicate the river was dammed (Giegengack, 1962). Flow is olivine basalt with euhedral quartz crystals, which at one time were in demand by collectors who thought they were diamonds. A shaft sunk into the crater floor in 1898 to a depth of 76 m to explore for diamonds was entirely in volcanic ejecta (Giegengack, 1962). Charcoal collected by Giegengack from an erect tree standing on the southeast edge of the crater rim that had been buried by ejecta and subsequently exposed in a quarry face gave a conventional ^{14}C age of 4,150±30 years BP, making this flow the youngest known volcanic rock in Colorado.

Pinkish low mesa to north across river is a remnant of a Pleistocene debris-flow fan. Other remnants occur downstream and across river. Fans appear to be graded to and locally built upon various Pleistocene terraces. Gradational and intertonguing character of Eagle Valley Formation can be observed in rocks that are well exposed on north valley wall. Paleozoic rocks to west comprise southeast flank of White River Uplift. Willow Peak, an undated, slightly eroded, possibly Holocene basalt cinder cone with associated flow, overlies nearly flat Paleozoic rocks on the White River Uplift. Retrace route on old US 6 & 24, continuing past I-70 underpass.

130.2 Cross Colorado River.

130.3 Stop sign at interchange on I-70 and Burns road, which follows Colorado River upstream to right. Continue west across Burns road, following what is now the frontage road on north side of I-70. Outcrops of Eagle Valley Evaporite on right.

131.1 **STOP 4. Examine contact between Eagle Valley Evaporite and Belden Formation.** Pull onto right shoulder just beyond turnoff for underpass. An unusually good exposure of the conformable contact between the Eagle Valley Evaporite and the underlying Lower Pennsylvanian Belden Formation occurs in the nearly vertical cut on the right near the underpass. The relatively sharp contact at this locality is at the base of the lower massive gypsum bed that rests on a sequence of interbedded black shale and clastic rocks. Locally occurring thin evaporite beds and gypsiferous clastic rocks near the top of the Belden Formation can complicate identification of this contact, particularly in areas of poor exposure.

The Belden Formation is a thick sequence of medium gray to black, and dark brown, calcareous, locally micaceous shale containing interbeds and lenses of grey limestone, claystone, mudstone, sandstone, conglomerate, and occasional thin beds of gypsum. Four or five beds of quartz-pebble conglomerate in the upper part of the Belden are widely traceable southeast of the White River Uplift.

The predominantly marine shales and limestones of the lower two-thirds of the Belden were the initial deposits in the Eagle Basin of the Central Colorado Trough, which formed as the Early Pennsylvanian sea flooded the karstic erosion surface that formed on Mississippian carbonate rocks. The Pennsylvanian Molas Formation, a regolith that formed on the erosion surface, is only locally preserved in this area. During early Belden time the Eagle Basin was bordered by broad lowlands which supplied moderate amounts of mud and silt (Mallory, 1971). Widening and increased subsidence of the Central Colorado Trough, concurrent with the beginning of uplift of the Front Range and Uncompahgre Highlands, are recorded in the clastic-dominated sediments of the upper one-third of the Belden. Coarse-grained sandstones and quartz-pebble conglomerate beds in this interval may correlate with clastic sediments of the lower Minturn or Gothic Formations which formed at the margins of the Eagle Basin from coarse detritus shed from these uplifts.

Lithology of the Eagle Valley Evaporite varies across the Eagle Basin. At the type section near Avon it is a light-colored gypsiferous mudstone and siltstone with some bedded gypsum and a few beds of limestone and shale. The Champlin no. 1 Black well near the town of Eagle penetrated 1,430 m of anhydritic gypsiferous mudstone and siltstone with halite casts and some bedded halite in the Eagle Valley Evaporite (Lovering and Mallory, 1962), whereas 16 km northwest of Eagle in the Benton well it is recognizable only as tongues of anhydrite 3 to 30 m thick in the Maroon Formation (Mallory, 1971). On the south and southeast flanks of the White River Uplift south of Glenwood Canyon and in the Cottonwood Creek area, the Eagle Valley Evaporite contains massive beds of white to gray gypsum with black sooty streaks and interbedded light-colored sandstones, siltstones, thin carbonate beds, and conglomerates. The Shannon no. 1 Rose well near the mouth of Cattle Creek drilled 630 m of gypsum, anhydrite, and siltstone, then 285 m of nearly continuous halite until the well was abandoned (unpublished lithologic log by American Stratigraphic Company; Mallory, 1972). The well was spudded near the crest of the Cattle Creek Anticline, which probably is a Laramide structure modified by salt diapirism and expansion due to hydration of anhydrite. The Mobile Elk Camp Federal well near New Castle encountered thick beds of anhydrite interbedded with clastic and carbonate rocks beginning at a depth of 4857 m (15,930 ft), but lost the well at 5314 m (17,430 ft) when halite began flowing into the hole (J. White, 1996, oral commun.)

In many areas the Eagle Valley Evaporite is slightly to severely deformed. Anticlines, synclines, recumbent folds, chevron folds, faults of various types, and diapirs that pierce into overlying formations have been observed. Along the Roaring Fork River just south of Cattle Creek, along Cottonwood Creek, and in the Eagle-Gypsum area, diapiric activity in the Eagle Valley Evaporite has domed and intruded the overlying Eagle Valley and Maroon Formations. Deformation associated with the evaporitic rocks only locally disturbed the underlying Belden Formation. At a few exposures beds of gypsum have mushroomed into or over Quaternary colluvial deposits, indicating Quaternary activity.

Thick sequences of evaporitic rocks crop out in the Eagle-Gypsum area and are also extensive in the Roaring Fork Valley near the mouth of Cattle Creek, leading Mallory (1971) to conclude that there were two primary evaporite depositional subbasins within the Eagle Basin. However, these two thick sequences are likely due at least in part to lateral flowage of evaporite from adjacent areas. DeVoto and others (1986) suggest that halite was deposited in a few other subbasins, but the halite encountered in the Mobile Elk Camp Federal well near New Castle demonstrates there either were more halite subbasins or they were larger than the ones proposed by Mallory or DeVoto and others. Since only a few wells provide subsurface data on the evaporite beds, our knowledge about their distribution is limited.

The Jacque Mountain Limestone and Robinson Limestone Members of the Minturn Formation, marker beds in the Middle Pennsylvanian of the Minturn/Gilman area, have been traced to Red Canyon on the west side of the Wolcott syncline 34 km east of here (Schenk, 1992). Carbonate beds mapped near the top of the Eagle Evaporite and in the overlying Eagle Valley Formation along Cottonwood Creek, in the Roaring Fork Valley, and west of Glenwood Springs may correlate with the limestone marker beds in the Minturn on the east side of the basin.

Low mesas to south across river are remnants of Pleistocene debris fans. Continue west on frontage road.

133.2 **LUNCH & STOP 5. Overview of White River Uplift, Glenwood Canyon, and lower Paleozoic stratigraphy.** Park at Glenwood Canyon trailhead at the upstream end of spectacular Glenwood Canyon. Southeast-dipping lower to middle Paleozoic sedimentary rocks exposed in the south flank of the White River Uplift are visible throughout the canyon. The uplift is a broad, elongate, roughly northwest-trending dome which has been subjected to at least one, and perhaps two major episodes of deformation. Both the White River Uplift and Grand Hogback Monocline were initially deformed during the latter part of the Laramide Orogeny in early to middle Eocene time. During a period of tectonic quiescence, an erosion surface was cut across the monocline and uplift. Both angular unconformities and disconformities separate older rocks from Neogene basalt sequences that rest on the erosion surface. Larson and others (1975) concluded that the region experienced alternating periods of basaltic volcanism and erosion from around 25 Ma through the Pliocene. Sporadic basaltic volcanism locally occurred during the Quaternary. According to their model, the older basalts should be found at higher elevations, whereas younger basalts should occupy floors of progressively younger paleovalleys. Hunt (1969) and Larson and others (1975) suggest that major tectonism, uplift, and associated cutting of canyons such as Glenwood Canyon began around 10 Ma. A remnant of the 0.62 Ma Lava Creek B ash (Izett and Wilcox, 1982) occurs immediately north of here (Bass and Northrup, 1963) less than 100 m above river level, indicating the canyon was cut to that level when the ash was deposited.

One topical study of the cooperative Colorado Geological Survey and U.S. Geological Survey mapping effort involves dating and correlating basalt flows on Dock Flats, on Sunlight Peak, on both sides of the Roaring Fork Valley between Glenwood Springs and Aspen, and especially those on Gobbler Knob and adjacent Spruce Ridge. Thin basalt flows on Spruce Ridge partly overlie the oldest known ancestral Colorado River gravels within Glenwood Canyon, which are located about 150 m below the rim of the canyon. Dating and correlating these rocks should greatly aid interpretations of the Neogene tectonic and geomorphic history of this region. Two $^{40}Ar/^{39}Ar$ dates obtained thus far during our mapping program apparently contradict existing theories. A 22 Ma basalt flow at the north end of Spring Valley lies only 320 m above the Roaring Fork River, while a 4 Ma trachyandesite eruptive center and associated flows occur on the south side of Dock Flats 850 m above the river!

About 7 km of Mesozoic and upper Paleozoic rocks have been eroded from the crest of the White River Uplift since the onset of uplift. Only a few small remnants of the Pennsylvanian Belden Formation are preserved on the structurally highest part of the uplift north of Glenwood Canyon. One of the perplexing problems related to establishing the age of uplift is the apparent lack of orogenic sediment that can be attributed to the uplift in the adjoining Piceance Basin. In that only moderately indurated clastic rocks, evaporitic rocks, and thin carbonate beds comprised nearly all of the erosionally stripped cover, it is not surprising that little coarse detritus has been found in Piceance Basin.

South of the Colorado River, on the lower, broad flank of the uplift, the Belden Formation, Eagle Valley Evaporite, and Maroon Formation crop out above the steep inner canyon walls of Glenwood Canyon. Late Tertiary basalt flows on Dock Flats cap this sequence south of the eastern half of the canyon. A basalt sample from the middle of the exposed sequence on Dock Flats has been submitted for whole rock $^{40}Ar/^{39}Ar$ dating, but results are not yet available.

Resistant rocks of the lower to middle Paleozoic "canyon series" and Proterozoic crystalline rocks form the spectacular cliffs in Glenwood Canyon. The 400-m-thick "canyon series" contains many unconformities. It represents only about 25% of early to middle Paleozoic time. Rocks of Devonian and Mississippian age are dominantly limestone and dolomite and are separated stratigraphically by unconformities. They are underlain by a more or less conformable sequence of clastic rocks which formed during the Early Ordovician and Late Cambrian. A major unconformity occurs between the Devonian-Mississippian rocks and Cambrian-Ordovician rocks.

Immediately beyond the trail underpass is an outcrop of light to medium gray, and bluish gray limestone and dolomite in the Mississippian Leadville Limestone. Limestone in the Leadville runs about 95% calcium carbonate and has been exploited for metallurgical, chemical, and environmental uses. It is fossiliferous, locally oolitic, and contains abundant black to dark brown chert nodules in its lower part. The Leadville Limestone consists of lithified oolitic and biogenic carbonate mud that accumulated on a stable, shallow-marine shelf. Red claystone and other fine-grained clastic rocks of the Molas Formation are recognizable in some outcrops here (see Table 1).

Note paleotower of Leadville which extends above the karst surface south of river from trail underpass. East of the paleotower locally tufa-cemented terrace gravels are overlain by dissected, Pleistocene debris-fan deposits that are exposed in railroad cuts. Active debris fans slope to the river.

A small hot spring issues from the Leadville on the south bank just above river level. This hot spring, along with several about 0.8 km upstream from here are collectively called Dotsero hot springs. They have temperatures around 32°C, a combined discharge in excess of 76 l/s, and total dissolved solids of around 10 g/l, of which about 3.5 g/l is sodium and 5 g/l is chloride (Barrett and Pearl, 1976; 1978). The salts are probably derived from halite in the Eagle Valley Evaporite. Dotsero hot springs, along with Glenwood hot springs, are major sources of dissolved salt loadings in the river. A proposed Colorado River desalinization project would remove salts from Dotsero and Glenwood hot springs before they enter the river.

The next unit below the Leadville Limestone is the Upper Devonian Chaffee Group. The Gilman Sandstone, upper member of the Chaffee, is medium to dark brown dolomitic sandstone whose sedimentological features suggest it formed both on land and in water. Identification of the Gilman is the only reliable way to locate the Leadville-Chaffee contact. Underlying the Gilman is the Dyer Dolomite, which is comprised of an upper dolomite (Coffee Pot Member) containing abundant rip-up clasts, bioturbated bedding, and stromatilitic algae, and a lower fossiliferous limestone (Broken Rib Member). Unit represents a cycle of transgression and regression of the Devonian sea, as stable shallow marine conditions were replaced by a muddy tidal-flat environment. Lowermost in the Chaffee Group are the shales, dolomites, and quartzites of the Parting Formation. Most prominent in the unit are two beds of brown-weathering quartzite which give this unit its popular name, the Parting quartzite. It formed in a shallow marine environment from sediments washed westward from the Front Range Highland.

Prevalent cliff-forming unit in middle of "canyon series" is the Ordovician Manitou Formation, which consists of two members. Magnificent fins of rock just down-canyon from here (also will be visible from highway) formed in highly jointed rocks of the Manitou. The upper member of the Manitou, the Tie Gulch Dolomite Member, is composed of brown, micritic, unfossiliferous, slightly siliceous, dolomite and minor limestone. It is a good marker bed, forming a distinctive orange-weathering cliff in canyon exposures. It was deposited in upper intertidal to lowermost supratidal (tidal-flat) environments. The Manitou's lower member, the Dead Horse Member, consists of flat-pebble limestone conglomerate, limestone, shaly limestone, and dolomitic orthoquartzite. The Dead Horse Member contains a diverse Lower Ordovician fossil fauna described by Bass and Northrup (1963). It formed in intertidal and shallow marine environments. Unconformable contact with the overlying Chaffee Group occurs at a thin shale bed which may be the remains of a paleosol (Soule, 1992).

Retrace route to stop sign on Burns road.

136.0 Stop sign at road to Burns. Turn right onto Burns road and turn right onto west-bound ramp on I-70.

138.9 Entering Glenwood Canyon. Descend stratigraphically through middle and lower Paleozoic and Precambrian rocks. Pullouts along highway are limited to rest areas, whose locations unfortunately were not selected for optimal geologic viewpoints!

Construction of I-70 through Glenwood Springs was a major engineering feat that took 13 years to complete at a total cost of $486,000,000. Rockfall is the primary geologic hazard in the canyon. Rockfall mitigation techniques include roadway grade or alignment change, rock scaling, ditches, rock bolting, steel netting and mesh, earthen walls, elephant-trap ditches, hanging chains, chime fences, flex-post fences, and submarine fences (R. Pihl, 1995, oral commun.). Rock scaling involves removal of loose rocks from a cliff by humans. Earthen walls reinforced with fabric are capable of stopping large, rapidly moving boulders and are faced with attractive masonry walls. Large excavated basins designed to catch falling rocks are known as elephant traps. A chime fence consists of closely spaced columns of stacked tires hung on vertical steel posts and are hidden from view by wooden fences. Horizontal cables strung between flexible posts comprise a flex-post fence. A submarine fence utilizes Navy-issue submarine netting, essentially heavy cable interwoven into a network of rings. A single innovative rubber tire wall was installed near the west portal of Hanging Lake tunnel. About 400,000 tires went into the fill and fabricated gum rubber blocks that face the wall. Unfortunately, the wall spontaneously caught fire in 1995 and may have been removed prior to this field trip. Another hazard in the canyon is falling ice, which builds up on steep rock faces next to the highway and then breaks loose. Strategic placement of hanging chains allows for ice to grow onto the chains, which helps support the icicles own weight.

141.0 Bair Ranch exit (#129). Immediately east of this rest area on the northern side of the canyon is a north to northwest-trending, asymmetrical anticlinal fold involving rocks of the entire “canyon series”. This fold, along with a similar fold on the east side of Grizzly Creek, are probably related to early deformation of the White River Uplift which involved east- to northeast-directed compressive stress. These north- to northwest-trending structures are truncated north of Glenwood and in Grizzly, and No Name Canyons by an extensive, east-west trending zone of reverse faulting, monoclinal folding, and graben development which may record a shift in direction and possibly intensity of the compressive stress field to more of a north-south component. This complex zone, which cuts across all north-northwest trending structures, is traceable along strike from the east end of Glenwood Canyon to west of the city of Glenwood Springs. It forms the main zone of structural deformation on the southeast flank of the uplift.

Basaltic gravels exposed on the opposite side of the river are interpreted to be debris-flow deposits from Ike Creek which grade to the top of and interfinger with Colorado River terrace gravels. Old landslide deposits fill valley on right, but were previously mapped as bedrock in a graben.

143.3 Cross major unconformity on top of Precambrian biotite-muscovite gneiss.

144.0 Entrance to Hanging Lake tunnel. Tunnel was bored through biotite-muscovite gneiss and biotite granite. Two large, north-trending faults were encountered in the tunnels, the easternmost of which had a 10-m-wide gouge zone and may be a reverse fault, based on its steep west dip (R. Pihl, 1995, oral commun.).

144.7 Exit from Hanging Lake tunnel. Note rubber retaining wall on right. Beds of gray silty clay of probable lacustrine origin were discovered in the eastern part of the canyon during the geotechnical exploration drilling program for I-70 (Bowen, 1988). These sediments may have been deposited in a lake dammed by rockslide debris from the south canyon wall just beyond the west end of Hanging Lake tunnel (R. Pihl and J. White, 1995, oral commun.). Conventional ^{14}C dates on organic material recovered from drill holes by the Colorado Department of Transportation suggest the lake existed from about 9,820±130 years B.P. to 3,890±120 years B.P. (J.B. Gilmore, 1996, written commun.)

144.8 Masonry-faced earthen wall on right.

147.1 Shoshone hydroelectric powerplant run by Public Service Co. of Colorado on right. Construction began in 1906. Water flows to plant from Shoshone dam through a 3.8-km-long bedrock tunnel. Canyon is cut about 450 m deep into Precambrian biotite granite in this section.

148.5 Grizzly Creek rest area exit (#121). Grizzly Creek canyon, which runs northward through the flank of the uplift, is every bit as spectacular as Glenwood Canyon with the added attraction of being relatively remote. Upper Grizzly canyon was glaciated during the Pleistocene. On the high ridge just east of Grizzly Creek, east of the Grizzly Creek Monocline, rocks of the Paleozoic “canyon series” are at their highest elevation above the Colorado River in Glenwood Canyon. This is the area of maximum uplift on the southern flank of the White River Uplift. About 3 km north of the highway Paleozoic rocks are displaced over 150 m vertically by the Grizzly Creek Fault. Surface observations indicate that it is a steeply dipping reverse fault with a broad zone of fracturing in Grizzly and No Name canyons, and that it is downthrown to the south.

150.4 Flex-post fence on right, with fault just beyond it.

151.4 No Name exit (#119). Red to yellow mudstones of Molas Formation on right immediately past interchange. The broad, gently sloping surface on which the rest area and community of No Name are built consists of a late Pleistocene debris-flow fan which overlies Pinedale terrace alluvium [Pinedale refers to the Pinedale glaciation, which occurred about 12,000-35,000 years ago (Richmond, 1986, chart 1A)]. Note how the Colorado River flows around the fan. Brush-covered slope across the river southeast of the exposed cliffs of Paleozoic rock is mantled with landslide and debris-flow deposits. The break in the Paleozoic "canyon series" cliff to the west near the tunnel marks the No Name Fault, which bounds the southwest side of the No Name Graben. On the south side of the river east of the rest area Paleozoic rocks are brought back to the surface on the upthrown south side of the graben. Minor folds and faults on the west side of the mouth of No Name Creek are associated with the Glenwood Canyon Monocline.

.152.3 No Name Fault, a normal fault which is downthrown on the northeast side (down to uplift) exposed to right of tunnel entrance. It displaces Leadville against Precambrian rocks on the southwest side of No Name Graben.

153.8 Leave I-70 at Glenwood Springs exit (#116). Turn right at stop sign at bottom of exit ramp. Turn right at next road (North River Road).

154.0 Entrance to Hot Springs Pool on left, an important location to remember, particularly if snowy weather shortens our days! Around a dozen springs collectively are known as Glenwood springs, including the largest hot spring in Colorado. They extend from about 0.8 km upstream to about 1.2 km downstream from the main pool area. Most springs are on the banks of the river at or slightly above river level, but two issue from blocks of Leadville Limestone that are out in the river! Combined discharge is around 170 l/s at temperatures of about 50°C, with total dissolved solids concentrations of 18-20 g/l including 6-7 g/l of sodium, 9-11 g/l of chloride, and 1 g/l of sulfate (Barrett and Pearl, 1976; 1978), which likely result from dissolution of halite and gypsum in the Eagle Valley Evaporite. Glenwood springs contribute more salinity to the Colorado River than to any other spring in the state and are the subject of a proposed desalinization project to improve Colorado River water quality.

154.4 Locked gate at Glenwood Canyon trailhead. Yampah vapor caves on left. Note caverns and enlarged joints in Leadville Limestone on both sides of river. Gabions and wire mesh on slope to left beyond the Leadville have met with mixed success in controlling colluvial processes on this hillslope. Route proceeds down-section through lower to middle Paleozoic canyon series. Formations passed include Leadville Limestone, Chaffee Group, Manitou Formation, Cambrian Dotsero Formation, and Cambrian Sawatch Quartzite.

154.6 Good exposure of the Parting Member of the Chaffee Group is exposed along railroad tracks on south side of the river.

154.9 Megablock of Manitou Formation rotated against northwest-trending normal fault across river. Railroad tunnel is cut into Upper Cambrian rocks, which in Glenwood Canyon and on the White River Uplift include the massive white and buff to gray-orange, brown-weathering, vitreous orthoquartzite of the Sawatch Formation and overlying sandy dolomites, dolomitic shale, limestone and dolomite conglomerates, and algal limestones of the Dotsero Formation.

Dotsero Formation consists of two members. Lower Glenwood Canyon Member is predominantly thin-bedded, glauconitic, sandy dolomite and limestone which form a gentle slope above cliffs of the underlying Sawatch Quartzite. Upper Clinetop Member is 1.5 m-thick and is composed of a matrix-supported limestone conglomerate with abundant rip-up clasts that is overlain by a thin bed of stromatolitic limestone with well preserved algal-head structure.

Sawatch Quartzite contains beds of massive orthoquartzite 0.3-0.9-m thick. Total thickness of the Sawatch Quartzite is 150 m. The upper part of the formation includes beds of quartzite and dolomite which may be correlative with rocks of the Peerless Formation. They may be unconformable with sediments of the underlying Sawatch Quartzite and with the overlying Dotsero Formation. Sawatch Quartzite formed as beach deposits in the littoral zone. Beds which may be Peerless equivalents formed in fluctuating conditions in the intertidal zone.

155.2 Precambrian porphyroblastic biotite of No Name canyon on left. Follow gravel road up along Cascade Creek. Pedestrian overpass for Glenwood Canyon trail heads to right over I-70.

155.4 **STOP 6. Examine No Name Fault and No Name Graben.** Park at loadout and walk up to road to water tank. Loadout located at lower end of aerial tram which served a recently active quarry in Leadville Limestone. Excellent exposure of No Name Fault in cut slope behind water tank. View to east from ridge above water tank looks southeast down the trace of No Name Fault into No Name

Graben. To the west the Paleozoic canyon series is cut off by the West Glenwood Fault. Both of these normal faults have significant dip-slip components with down-to-the-north throw that is opposite of the regional uplift pattern. They may be related to extensional tectonism which post-dates the compressional Laramide Orogeny. Structural studies currently underway will attempt to correlate and interpret faulting and folding on the south flank of the White River Uplift.

Retrace route past locked gate and Yampah vapor caves.

156.5 Intersection of North River Road and 6th Street. Continue ahead on 6th Street to stoplight at Grand Avenue. Continue through intersection and get into middle lane.

156.8 Turn left at stoplight at 6th and Laurel Streets; then turn right onto westbound I-70. Confluence of Roaring Fork and Colorado Rivers on left. Glenwood Springs lies at structural junction of Grand Hogback Monocline and main zone of deformation on south flank of White River Uplift.

157.6 Cross West Glenwood Fault. Hobo and Iron hot springs occur along this fault near river to left. Storm King Mountain at 1 o'clock. To left across river is Red Mountain fan, an active debris fan derived from Maroon cliffs. Thin, weathered basalt flow caps the redbed cliffs. Note sinkhole near east edge of fan, where underlying bedrock is Eagle Valley Evaporite. Past irrigation on the fan has caused the sudden development of sinkholes, most of which were subsequently filled with trash and covered with soil so farming could continue. Future debris flows, new sinkholes, and low-density, uncompacted fill placed in old sinkholes pose engineering problems for the new by-pass route being constructed at the toe of the fan.

158.7 West Glenwood exit (#114). The 1994 South Canyon forest fire burned to ridgeline at 1 o'clock, nearly encroaching into West Glenwood.

159.7 Entering Grand Hogback Monocline. Steeply dipping Eagle Valley Formation exposed in roadcut on right. Maroon Formation on hillslope to left across river. Hillslopes to right burned during South Canyon fire.

160.3 Mouth of Basin F (Cannon and others, 1995), which generated debris flows that temporarily blocked I-70 in 1994 and 1995.

161.7 South Canyon Creek exit (#111). Bull Lake terrace gravels in roadcut to right and across river to left [Bull Lake refers to the Bull Lake glaciation, which occurred about 140,000-150,000 (Pierce, 1979) or 130,000-300,000 years ago (Richmond, 1986, chart 1A)].

162.7 Pinedale terrace gravels on right.

163.1 Thin sliver of fault block within Maroon Formation preserved in roadcut on right.

164.1 Leave I-70 at Canyon Creek exit (#109). Turn right at stop sign onto frontage road on north side of I-70.

164.4 Turn left onto Canyon Creek Road (CR 137).

164.7 **STOP 7. Overview of Storm King Mountain and a structural terrace on its south flank.** Park at school bus turnaround. Note steeply south-dipping beds on ridgeline near I-70 that roll over and become generally flat lying along a faulted fold near the ridge crest. Structural terrace extends north to base of mountain, where another fault/fold complex terminates the terrace against slightly overturned beds in Maroon and Eagle Valley Formations. Late Tertiary limestone conglomerate rests on angular unconformity over Maroon on southeast shoulder of Storm King Mountain. A huge ancient landslide complex lies on part of the structural terrace, but fortunately was not reactivated after the fire. Thick deposits of colluvium and slopewash in some basins on the structural terrace were deeply dissected prior to the 1994 fire. Continue north on Canyon Creek Road.

165.1 Steeply south-dipping beds in Maroon form fins on hillslope on right. These beds are overturned with steep northerly dips near ridge crest. Overturning becomes more pronounced towards north, with bedrock along entire hillside being overturned.

166.1 **STOP 8. View conglomerate at Canyon Creek and Pleistocene moraines.** Park at wide shoulder area overlooking Peach Valley Arabian ranch. The conglomerate of Canyon Creek is exposed on both sides of the valley at this location. It is predominantly a clast-supported cobble conglomerate containing angular to subrounded clasts of Pennsylvanian and older rocks. Clast content varies with location. Clasts of Proterozoic basement rock occur only locally; lower Paleozoic rock clasts dominate locally, but Pennsylvanian clasts dominate in many exposures. Larger clasts are generally 0.2-0.4 m in diameter, but reach a maximum diameter of one meter. In detail, bedding is poorly developed except for local lenses of sandstone or pebbly sandstone. Stratigraphic facing criteria are rare. Apparent thickness of unit is about 200 m.

The conglomerate appears to form a syncline 6 km long and 1 km wide as Bass and Northrup (1963) concluded. However, the trough of the syncline is covered by surficial deposits. The south limb of the syncline is locally overturned to the north. At Canyon Creek the south limb of the syncline appears to be concordant with the underlying Eagle Valley Evaporite. This may be why the conglomerate east of Canyon Creek was shown to be Pennsylvanian by Tweto and others (1978). They called the conglomerate west of Canyon Creek the Miocene Browns Park Formation. The conglomerate west of the creek has the same sedimentological and structural characteristics as that east of the creek. West of Canyon Creek the conglomerate on the north limb of the syncline is clearly unconformable on the Pennsylvanian rocks.

Thus the two favored hypotheses for the age of the conglomerate at Canyon Creek are Pennsylvanian or Miocene. Nowhere else in the Pennsylvanian-Permian section is there a conglomerate known to have the texture and thickness of that at Canyon Creek. Pennsylvanian-Permian conglomerates contain rounded to subrounded pebbles and cobbles in this area, and even near the basin margins conglomerate clasts are better rounded than those at Canyon Creek. Conglomerates in the late Paleozoic section tend to be matrix supported and more variable in clast size and proportions of matrix.

Locally derived conglomerates are absent in the Mesozoic section nearby. Lower Tertiary rocks of the Wasatch Formation are conglomeratic, and distribution and clast content indicate derivation from the Sawatch Uplift rather than the White River Uplift. Upper Tertiary units contain conglomerates derived from nearby uplifts. The outcrops of Neogene sedimentary rocks closest to Canyon Creek are of siltstone, claystone, sandstone, and volcanic agglomerate interbedded with Miocene (?) basalt 10-20 km to the southeast.

We tentatively agree with Bass and Northrup (1963) and assign a Miocene age to the conglomerate at Canyon Creek. Better dating would help us evaluate the structural significance of the conglomerate. Its synclinal structure was attributed to dissolution of underlying evaporite by Bass and Northrup (1963). Would such a process produce a well defined and laterally continuous syncline? Does the conglomerate have a different structural story to tell us?

The bouldery, hummocky landforms to the north are part of a large system of lateral and terminal moraines that were deposited during one or more Pleistocene glaciations. These moraines were deposited by a glacier or glaciers that flowed from the White River Uplift down the valley of Canyon Creek to an elevation of about 1,800 m, 2.7 km north of the Colorado River. The well preserved depositional morphology of these terminal moraines suggests that they formed during the Pinedale glaciation about 12,000-35,000 years ago (Richmond, l986, chart 1A). Limited exposures indicate that they are probably composed primarily of unstratified till that is matrix supported and locally clast supported. The matrix of the till is calcareous, slightly silty, very fine to very coarse sand. Clasts in the till are mostly angular to rounded and include gneiss, schist, amphibolite(?), dolomite, limestone, quartzite, sandstone, and basalt. Some of the dolomite clasts are soled and striated; some of the gneissic boulders on the moraines are as much as 6 m in length. The till and other glacial deposits may be as much as 150 m thick in the high lateral moraine about 1.2 km northwest of here. The post-glacial sediments that accumulated in the valley of Bearwallow Creek, which is blocked by this moraine, may be as much as 90 m thick (Fairer and others, l993). Retrace route to Canyon Creek interchange on I-70.

167.9 Turn right onto westbound I-70.

169.1 Dakota Sandstone caps ridge on left. Area at river level enclosed by chain link fence contains dinosaur fossils in Morrison Formation.

170.0 Entering strike valley in Upper Cretaceous Mancos Shale. Upper Cretaceous Mesaverde Group comprises prominent ridge to left across river. Note coal loadouts and waste piles associated with mines that worked Mesaverde coal beds beginning in the late 1800’s. Hazardous openings at these mines have been safeguarded by Colorado Inactive Mine Program. Linear unvegetated zones parallel to bedding mark actively burning coal beds. At least two of the mines which worked this area were closed due to fires, and two or more seams continue to burn (Rushworth and others, 1989). Several other active Mesaverde coal fires are burning near New Castle, in South Canyon, and along Fourmile Creek. Pinedale terraces overlain by fan deposits across river.

171.4 Leave I-70 at New Castle exit (#105). Turn right at bottom of exit ramp; turn left at stop sign on US Highway 6; proceed through New Castle.

173.5 Southwest-dipping beds in Mesaverde Group to right.

174.5 Approximate location of synclinal axis that separates Grand Hogback Monocline on east from Piceance Basin to west.

175.1 To right two white sandstone beds and pinkish interbed probably part of paleosol formed on erosion surface cut into Mesaverde Group. Paleosol overlain by mudstone and conglomeratic sandstone with volcanic and hypabyssal clasts in basal Eocene-late Paleocene Wasatch Formation.

176.4 Turn left on river frontage road; cross railroad tracks and I-70.

176.5 **STOP 9. Overview of mesas and terrace remnants.** Turn left at “T” intersection and and park on shoulder. This stop provides us with views of the mesas and terrace remnants on the south side of the Colorado River and of the terrain typical of the

Piceance Basin. Roan Cliffs to west are capped by Eocene Uinta and Green River Formations, which overlie the Wasatch. Parachute Creek Member of Green River Formation is famous for thick beds of oil shale.

About l5 km to the southwest there are three prominent geomorphic surfaces. From lowest to highest, these surfaces are Hunter Mesa, Grass Mesa, and Flatiron Mesa. Grass Mesa and Flatiron Mesa are south of Rifle; Hunter Mesa is on the east side of Grass Mesa. Hunter Mesa is underlain by thin (probably less than 10 m) pediment deposits that appear to be graded to Colorado River terrace deposits that are about 50 m above the river. Grass Mesa is underlain by a thick (about 35-65 m) sequence of old debris-flow deposits and minor amounts of interstratified stream alluvium. These deposits thin to the south and locally overlie Colorado River terrace deposits that are about l80 m above the river. A 100-cm-thick soil K horizon with massive and laminar (stage III and IV) carbonate morphology is formed in stream alluvium at the top of the sequence. No buried soils were observed in the underlying deposits. The lower limit of Grass Mesa is about 245-260 m above the Colorado River. Flatiron Mesa is underlain by a thick (about 60 m) sequence of old debris-flow deposits (Stover, 1993). These deposits overlie Colorado River terrace deposits that are about 610 m above the river. The lower limit of Flatiron Mesa is about 670 m above the Colorado River. All three of the above mesas are mantled by one or more loess sheets (Shroba and others, 1994, 1995). Loess sheets on terraces and other gently sloping geomorphic surfaces along the Colorado River between Glenwood Springs and Rifle are commonly 1-3.5 m thick. Unweathered loess is calcareous, slightly clayey, sandy silt. The relatively high content of very fine sand plus coarse silt (55-65 percent) and the relatively high coarse silt/total silt ratios (about 0.7) of the unweathered loess suggest (1) a relatively short distance of eolian transport and (2) flood plains of the Colorado River and its major tributaries are likely sources of much of the loess (Shroba, l994).

Due south of here is a prominent, unnamed, geomorphic surface that is underlain by fan alluvium and valley-fill or pediment(?) deposits. These deposits consist of old, basalt-rich, stream alluvium and debris-flow deposits that are well exposed in the large landslide scarp visible near the top of the surface. They are about 45 m thick in the scarp and probably thin toward the south. They overlie Wasatch Formation and may locally overlie Colorado River terrace deposits. The stream alluvium and debris-flow deposits are overlain by at least five loess sheets that accumulated during episodes of eolian activity. The lower four loess sheets contain buried soils that formed during episodes of landscape stability. A 120-cm-thick soil K horizon with stage III and IV carbonate morphology formed in the top of the basalt-rich deposits prior to loess deposition. The lower limit of the surface is about 275 m above the Colorado River. Steep slopes underlain by the Wasatch Formation are prone to landsliding. Earth-slump and earth-flow deposits are common on the east flank of this surface (Green and others, l993).

About 3 km to the east there are three loess-mantled, terrace remnants that are about 40, 80, and 115 m above the Colorado River. Sediments in the lower two terrace remnants were deposited by the Colorado River. They consist primarily of cobbly, pebble gravel of mixed lithology that is about 20 m and 3 m thick, respectively. Sediments in the highest terrace remnant were deposited by Garfield Creek. They consist of bouldery, basalt-rich gravel about 4 m thick (Green and others, l993).

END OF DAY 1. RETURN TO GLENWOOD SPRINGS.

Day Two

0.0 Depart Silver Spruce motel. Turn left onto US Highway 6 & 24 (6th Street)

0.2 Abandoned quarries in Leadville Limestone on right.

0.4 Leadville faulted against Eagle Valley Evaporite along West Glenwood fault. Note complex structures in roadcuts for next 0.5 km.

0.8 In roadcuts on right Bull Lake terrace gravels interfinger with and are overlain by older debris-flow deposits and capped by a veneer of loess. Ledge of tufa caps terrace deposits northwest of here. Recently excavated home foundation into base of the tufa ledge encountered hot water, causing problems for developer.

2.0 Stoplight at intersection of US Highway 6 & 24 with Mel-Ray Road. Proceed through intersection on US Highway 6 & 24.

2.7 Steeply dipping beds in Eagle Valley Formation exposed in roadcut on right.

3.2 Mouth of Basin H of Cannon and others (1995). Note trees on hillslopes to right that were burned by the South Canyon forest fire. Debris was flushed from Basin H onto the county road and I-70 during debris-flow events in 1994 and 1995.

3.3 **STOP 1. Walk up debris-flow channel that carried debris during floods in 1994 and 1995, subsequent to the South Canyon forest fire.** Park at

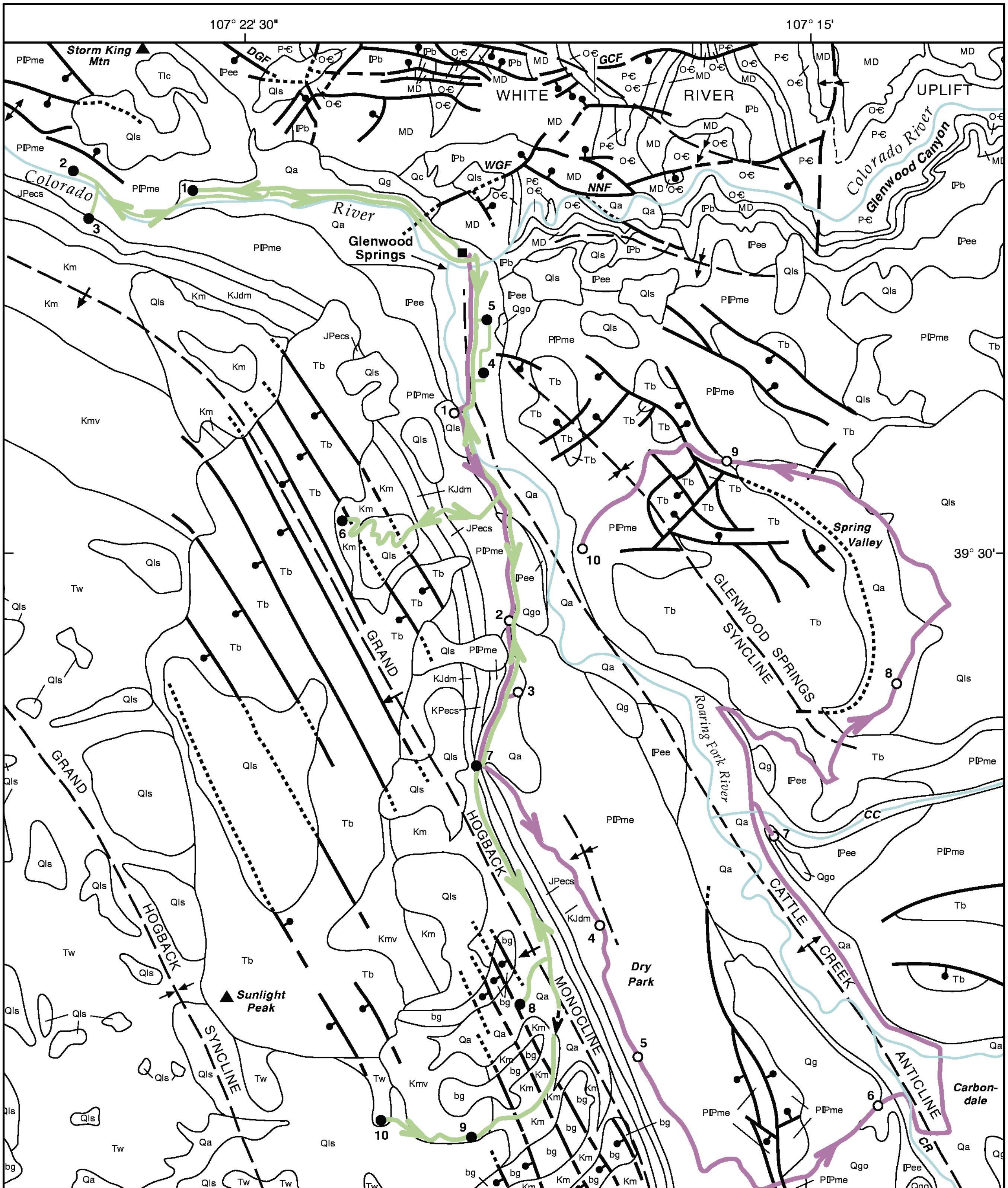
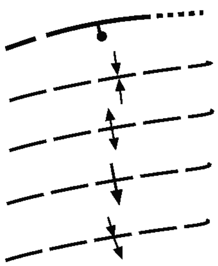


Figure 5. Generalized geologic sketch map of the Glenwood Springs area, showing field trip route and stops on Days 2 and 3.

Units

Qa	Holocene and Pinedale alluvium, and overlying colluvium, debris-flow deposits, and Loess
Qg	Bull Lake alluvium and overlying colluvium, debris-flow deposits, and Loess
Qgo	Pre-Bull Lake alluvium and overlying colluvium, debris-flow deposits, and Loess
Qls	Quaternary landslide deposits
bg	Early Quaternary and late Tertiary high-level basaltic gravel
Tlc	Late Tertiary limestone conglomerate
Tb	Late Tertiary basalt
Tw	Eocene and Paleocene Wasatch Formation
Kmv	Upper Cretaceous Mesaverde Group
Km	Upper Cretaceous Mancos Shale and Frontier Sandstone and Lower Cretaceous Mowry Shale
KJdm	Lower Cretaceous Dakota Sandstone and Jurrassic Morrison Formation
JPecs	Jurrasic Entrada Sandstone, Triassic Chinle Formation, and Triassic (?) and Permian State Bridge Formation
P₽me	Permian and Pennsylvanian Maroon Formation and Pennsylvanian Eagle Valley Formation
₽ee	Pennsylvanian Eagle Valley Evaporite
₽b	Pennsylvanian Belden Formation
MD	Mississippian and Devonian rocks, undivided
O-Є	Ordovician and Cambrian rocks, undivided
P-Є	Precambrian rocks, undivided

Structures



Fault; dashed where approximately located; dotted where concealed

Syncline; approximately located

Anticline; approximately located

Monocline; axial trace; approximately located

Monocline; synclinal limb

CCA	Cattle Creek Anticline	***CR***	Crystal River
DGF	Dolan Gulch Fault	***CC***	Cattle Creek
GCF	Grizzly Creek Fault	***CD***	Carbondale
GHM	Grand Hogback Monocline	***DP***	Dry Park
GSS	Glenwood Springs Syncline	***GS***	Glenwood Springs
NNF	No Name Fault	***SKM***	Storm King Mountain
WGF	West Glenwood Fault	***SLP***	Sunlight Peak
		SPV	Spring Valley

■ Silver Spruce Hotel

Field Trip Route on day 2, arrows show direction of travel and solid circle indicates stop

Field Trip Route on day 3, arrows show direction of travel and open circle indicates stop

Figure 5. Explanation.

parking area for driving range. Private property. South Canyon fire burned slowly for several days before exploding into a fire storm on July 7, 1994 as a cold front passed through. Fourteen firefighters were killed in the blazing inferno, which burned about 8 km2 of pinyon, juniper, and gambel oak on the south side of Storm King Mountain. Temperatures were locally high enough to melt and fuse quartz grains in soil. Ash and loose soil accumulated in the bottoms of drainages as dry ravel subsequent to the fire (Cannon and others, 1995). Torrential rains the night of September 1, 1994 created floods which washed debris onto I-70 at four locations as a slurry of mud, rocks, and burned trees. Detailed (1:5,000 scale) mapping of the burn area indicates most debris mobilized during the 1994 event was derived by 1) flushing out dry-ravel deposits that had accumulated on the channel floors, 2) erosion of older surficial deposits including previous debris-flow deposits, landslides, and colluvium/slopewash immediately adjacent to the channel floors, and 3) rilling, minor gullying, and debris avalanching of loose surficial deposits on steep slopes cut into old landslide deposits, old valley-filling colluvium/slopewash, and Maroon bedrock (Kirkham and others, 1996). Thirty vehicles were trapped by the debris flows, including a few which were carried into the river. Fortunately, there were no deaths and only minor injuries resulting from the debris flows.

Although the burn area was aerially seeded in November, 1994, additional debris flows poured out of Basin F during 1995. The revegetation effort was very successful on gentle slopes where the original soil profiles were preserved, but steep slopes are revegetating poorly due to absence of productive soil horizons and removal of seed by sheetwash during rainstorms prior to sprouting. On a positive note, burned oakbrush is rapidly developing new shoots which "sucker up" from roots. Abundant unconsolidated materials remain within these basins and will be susceptible to mobilization during future storm events. A few small landslides have moved since the last debris flows in 1995 and partially block drainage channels. No evidence was observed to indicate large-scale reactivation of the huge, old landslide complex.

Retrace route back to stoplight at US Highway 6 & 24 and Mel-Ray Road.

4.6 Turn right onto Mel-Ray Road, then right onto westbound I-70. New Midland Avenue by-pass around downtown Glenwood will eventually tie to this interchange.

8.5 Leave I-70 at South Canyon exit (#111).

8.6 **STOP 2. Example of how debris-flow hazards may be mitigated, and secondary deformation within the Grand Hogback Monocline.** Park on shoulder at bottom of ramp. Debris flows ran out of Basins C and D of Cannon and others (1995), but were intercepted by the ramps on I-70, which diverted the debris to the underpass beneath I-70, effectively mitigating the hazard to traffic on the highway. Fascinating exposures of structural features associated with the south limb of the structural terrace crop out a short distance up Basin C. Anticlinal folding in beds adjacent to a fault is interpreted as fault drag, implying fault throw was down to the north, opposite of regional uplift trends. On opposite side of drainage nearly horizontal faults are present. A flat-lying fault in Basin B is, based on folding interpreted as fault drag, either a very low-angle normal fault or a high-angle fault that later was rotated.

Turn left on South Canyon Road (CR 134) at stop sign at bottom of exit ramp.

9.3 **STOP 3. Exposures of Pennsylvanian to Jurassic rocks**. Park on shoulder. Excellent outcrops of the section from Maroon through Entrada. Measured sections at this locale are contained in several references. Type locality of South Canyon Creek Member of State Bridge Formation (Bass and Northrup, 1950; Stewart and others, 1972).

Return to I-70 interchange and turn right onto eastbound I-70.

13.6 I-70 is on a Pinedale terrace capped by thin veneer of debris-flow deposits. Along the river below the rest area the terrace deposits, whose upper surface lies 5.8 m above river level, are overlain tufa which contains an interbed of peat that yielded a conventional ^{14}C date of 12,410±60 years BP (D. Trimble, 1995, written commun.; USGS-3544), providing a minimum age for a youngest Pinedale terrace on the Colorado River.

14.3 Large blocks of white marble in stockpile next to railroad across the river are from Yule quarry and await shipment to overseas cutters.

14.9 Leave I-70 at Glenwood Springs exit (#116). Turn left at stop sign at bottom of ramp, following signs for Highway 82. Turn right at stoplight onto 6th Street, turn right at stoplight onto Grand Avenue, and continue through downtown Glenwood Springs. Grand Avenue climbs uphill as it crosses distal end of Cemetery Gulch fan. Turn left at 23rd Street, ascending fan. Turn left on Blake Street.

17.0 **STOP 4. Discuss historic debris flows.** Park at 21st and Blake Streets. About 20 damaging debris flows and hyperconcentrated flows have hit Glenwood Springs this century. On July 24, 1977 about 80 hectares (ha) of the city, including this quiet neighborhood, was inundated by rocks, mud, and uprooted trees, burying yards and streets, filling basements, and breaking windows. Damage and cleanup costs were estimated at about $2,000,000. Potential mitigation techniques include channelization, catchment basins, and diversion berms, however these are difficult to implement in an urbanized area. Follow Blake Street around hospital. Turn right on 13th Street, then left on Bennett Street.

17.8 **STOP 5. Overview of structural geology and geologic hazards of the Roaring Fork Valley.** Park at trailhead for Pioneer Cemetery at 12th and Bennett Streets. Walk up road to cemetery following 12th Street drainage canal. Construction of canal was undertaken in 1930's as a WPA project to handle debris flows out of Cemetery Gulch, which had damaged the city several times in prior years. Pioneer Cemetery, in which Doc Holliday is buried, lies on an topographically high remnant of an early(?) Pleistocene debris-flow fan and provides an excellent vantage point of the Roaring Fork Valley.

The Grand Hogback Monocline separates the White River Uplift from the Piceance Basin. At Glenwood Springs a zone of faulting and folding, which accounts for much of the structural relief on the uplift, splits from the monocline. The fault zone runs east through or just north of Glenwood Canyon. The monocline trends generally south from Glenwood to near Redstone, where it becomes a thrusted structure. Between the Roaring Fork Valley and the east-trending structural zone in Glenwood Canyon, the White River Uplift consists of jumbled slabs of faulted basalt underlain by Maroon and older rocks that generally dip gently south. The monocline forms the eastern margin of the Piceance Basin in this area and is bounded on the east by Cattle Creek Anticline, whose structural closure is in part due to salt diapirism. Along Roaring Fork Valley subtle Glenwood Springs Syncline and associated faults separate Cattle Creek Anticline from the White River Uplift (Figure 4).

Rocks dislodged from Maroon cliffs on both valley walls create hazards for humans below. Large landslide across river and to left involves Maroon and Eagle Valley Formations. Toe of this slide has been partially removed along Midland Avenue, apparently without reactivating it. Bedrock formations most prone to landsliding include Wasatch, Mancos, Belden, Maroon, Eagle Valley, and Morrison. Continue north on Bennett Street. Turn left on 11th Street., turn left on Grand Avenue, turn left on Hyland Park Drive, and stop for **LUNCH** at Sayre Park. After lunch continue uphill on Hyland Park Drive, turn right on Blake Street, go around hospital, and turn right on 23rd Street.

19.3 Cross Grand Avenue on 23rd Street. Turn right on 27th Street and cross Roaring Fork River using Sunlight Bridge. 27th Street bends to south and merges with Midland Avenue just past bridge. Note small debris-flow fans and rockfall hazards along west valley wall. Roaring Fork Valley follows axis of Cattle Creek Anticline.

19.9 Roadcut on right into toe of landslide is currently stable except for rocks falling out of cut slope. Pinedale terrace on left across river.

20.8 Turn right on Threemile Road (CR 127), which heads west cutting through the Grand Hogback Monocline. Continue on main road, climbing through two switchbacks. Green pipe gate with no trespassing sign marks beginning of private road.

22.1 Schoolhouse Member of Maroon on right. Over next 300 m typical poor exposures of the Schoolhouse, State Bridge, Chinle, Entrada, and Morrison rocks can be seen.

22.4 Dakota Sandstone forms prominent outcrop, but overlying Mowry Shale, Frontier Sandstone, and Mancos Shale are generally covered by colluvium and landslides.

22.6 First of a series of switchbacks as road ascends this unstable slope.

23.7 Entrance to Mountain Springs Ranch.

24.4 Unstable landslide that damages road during wet springs.

25.2 **STOP 6. Discuss faulted basalt cap on Sunlight Mesa.** Park on shoulder. Private land. To southwest is Sunlight Peak and Sunlight Mesa, which are capped by basalt flows and interbedded sediments informally called the Sunlight volcanic sequence. The lowermost exposed flow near Sunlight Peak has been sampled for $^{40}Ar/^{39}Ar$ dating. Slope extending northeast from peak is faulted dip slope of volcanic rocks. Mount Sopris and Elk Mountains to south are middle Tertiary calc-alkaline igneous intrusions. Basalt Mountain to southeast is an eroded shield volcano dated at 8.78±0.4 Ma (Larson and others, 1975).

Cretaceous rocks exposed along Threemile Creek are deformed by the Grand Hogback Monocline and now dip 40-60° west. Subsequent to this folding at least 1.5 km of overlying sedimentary rocks were stripped by erosion, and a relatively horizontal erosion surface was created. The Sunlight volcanic sequence was erupted onto this flat surface. We believe the monoclinal folding occurred late during the Laramide orogeny in Eocene time. The erosion surface may have been carved during the late Eocene, a period of widespread erosion in Colorado (Epis and Chapin, 1975; Scott, 1975) or perhaps during the Miocene, similar to that described by Steven and others (1995). Obviously, the age of the Sunlight volcanic sequence is a key piece of evidence that we anxiously await.

The originally flat mesa capped by the Sunlight volcanic sequence was later disrupted by a series of northwest-trending normal faults which parallel bedding within the underlying folded sedimentary rocks. We are standing on the trace of a fault which displaces the basalt cap about 100 m down to the west. Cumulative throw on the entire series of faults approaches 300 m, all down to the west. In contrast to the fault displacements, tilting of Sunlight Mesa is to the east. The mesa loses over 1000 m of elevation between Sunlight Peak and the west wall of Roaring Fork Valley. Note the overall bowl-shaped character of the mesa and the large landslide complex within the bowl. The head of the bowl coincides with the only fault on the mesa that is downthrown to the east. The landslide complex is developed in sediments which appear to overlie the basalt.

Murray (1969) suggested these bedding-plane faults were related to relaxation of the moncline. Unruh and others (1993) believed they are due to flowage of evaporitic rocks from beneath this part of the monocline. Tilting of the mesa and its bowl-shape appear to provide additional support to the model of Unruh and others (1993), but the steep dip slope of basalt between Threemile and Fourmile Creeks a short distance above the Roaring Fork River complicates their theory.

Continue up subdivision road to next road intersection where the vehicles can turn around; Retrace route to Midland Avenue.

30.7 Turn right on Midland/Fourmile Road (CR 117).

31.0 Take right hand fork of "Y" intersection, following signs to Sunlight ski area.

33.3 Road on older debris fan associated with Fourmile Creek. Note size and abundance of basalt boulders in yards and along road. Ridge on right capped by Dakota Sandstone which was deposited in a transgressive coastal plain environment; Morrison, Entrada, Chinle, and State Bridge crop out on slope, but exposures are poor.

34.2 **STOP 7. Outcrop of Dakota Sandstone.** Park on left shoulder well beyond Glenwood Springs Emergency Services Station #4. As seen in the water gap of Fourmile Creek, resistant Dakota Sandstone forms good outcrops and protects the hogback ridge from erosion. Mancos Shale strike valley to west is cut by Fourmile Creek, which generally flows eastward through monoclinally upturned Wasatch and Mesaverde rocks until it encounters the Dakota hogback and swings north cutting the Mancos strike valley until reaching this water gap. Note abundant landsliding in Mancos hills, particularly to north, where they spill over the ridge crest. Basins draining hills to west are filled with heavily forested colluvial and landslide deposits that grade to debris flows downvalley. Continue south on Fourmile Road, which parallels excellent exposures of the Dakota dip slope.

35.3 Note prominent ribs of Mesaverde sandstone beds in foothills to right of creek.

37.0 **STOP 8. Faulted late Pleistocene debris-flow deposits.** Turn right on gravel road leading to barns at Argonaut Farm and park near stables. Private land. Walk to fault scarp in debris-flow deposits. Hills to north and south are capped by late Tertiary or early Quaternary basaltic gravels deposited on gently east-sloping surfaces as pediment or valley-fill deposits. Based on its only good exposure, this unit is slightly lithified and its basalt clasts are very weathered. These gravels are downthrown to the west by the same series of northwest-trending faults that offset basalt flows at Stop 6. Displacements in basaltic gravels are less than those in the basalt flows, suggesting recurrent fault movement. Subtle scarps along two or three of these faults are preserved in late Pleistocene debris-flow deposits which fill this unnamed tributary valley. Retrace route to Fourmile Road and turn right.

37.7 Cross Fourmile Creek.

38.5 Mesa on skyline at left consists of Mancos Shale overlain by veneer of late Tertiary/early Quaternary basaltic gravels that are downthrown to west by bedding plane faults. Note small landslides that disrupt irrigation ditch below top of mesa.

39.1 Landslide on left side of creek. Note thick grove of aspens, which locally exhibit pistol butting and characteristics of a "drunken" forest that has been displaced downslope.

39.2 Cozette sandstone member of Upper Cretaceous Mesaverde Group exposed in road cut on right. This 15 m-thick, tan to gray, equigranular sandstone is the uppermost of a series of regressive sandstones in the Mancos Shale. These sandstones record pulses or cycles of advancing and receding shorelines in this area during Late Cretaceous time. At least two stratigraphically lower sandstone beds, the Corcoran and Sego (?), which are similar to the Cozette in that they display Mesaverde-like characteristics, probably are present in this valley. The Corcoran crops out south in Marion Gulch, but in this valley these lower sandstone beds are covered.

39.5 Prominent sandstone bed on horizon to right is the middle sandstone of the Bowie Shale Member of the Mesaverde Group. Lower down, concealed by brush is the Rollins Sandstone Member. Between these two sandstone beds lie the most productive coal beds of the southern Grand Hogback. Note that the sandstones of the Rollins Member are frequently burnt red by outcrop fires which occur in the overlying coal beds. Coal was produced from four prominent beds in this zone, which is called the Cameo-Wheeler-Fairfield coal zone.

39.6 Road to Sunlight coal mine on right. This mine produced a reported total of 189,032 metric tons of low-sulfur coal from 1901 to 1975. Coal rank was bituminous with a heat value of 12,150 to 12,684 Btu/lb (Boreck and Murray, 1979). Hazardous openings associated with this mine have recently been safeguarded by the Colorado Inactive Mine Program. Rollins Sandstone is visible adjacent to the road.

39.7 The middle sandstone of the Bowie Shale Member, a 21-m-thick, gray, fine- to medium-grained, massive sandstone, crops out in this roadcut and is traceable northward for several kilometers. Near the Black Diamond coal mine it disappears underneath the basalt cap on the northeast flank of Sunlight Peak. A productive coal zone is directly above the middle sandstone of the Bowie Member in South Canyon Creek north of here, but is not recognizable in this outcrop. This sandstone was deposited in varying environments of the delta-front zone dominated by distributary mouth bar, bar-finger sand, subaqueous levee, and interdistributary bar-beach sand styles of sedimentation (Collins, 1976).

39.8 **STOP 9. Examine outcrop of upper sandstone of the Bowie Shale Member of the Upper Cretaceous Mesaverde Group.** Park on left shoulder. The 15-m-thick, gray, massive upper sandstone is the uppermost bed in the Bowie Shale. It is similar in lithology and mode of deposition to the middle sandstone. The sequence of shale and coal beds directly above the upper sandstone are included in the Paonia Shale Member of the Mesaverde Group. The upper member of the Mesaverde Group includes the Paonia Shale Member and an overlying package of Upper Cretaceous rocks. Production from this coal zone has been much less than that from the Wheeler-Cameo-Fairfield coal zone, because the seams are thin. Note reddish beds of clinker and baked sandstone associated with outcrop fire in these coal seams. Continue west on Fourmile Road.

40.0 Turn right at “T” intersection, following Fourmile Road (FR 300).

40.7 Sunlight ski area to left across creek.

41.0 **STOP 10. Outcrop of Wasatch Formation.** Park in trail area on right (marked by USFS boundary signs) and walk up Fourmile Road. West-dipping, gray, maroon, and red-brown conglomeratic sandstone beds in basal Wasatch Formation (Paleocene?) are exposed in roadcut. Clasts include volcanic and hypabyssal rocks probably derived from Sawatch Range during early Laramide uplift of the range. Syncline at base of Grand Hogback Monocline lies about 3.5 km to west. Wasatch-Mesaverde contact obscured by landslides and colluvium in basin to east, hence occurrence of regolith or paleosol at top of Mesaverde cannot be documented here. Anomalous knob on south flank of Sunlight Peak may be an eroded basaltic vent, but is mapped as basaltic gravel. Note preponderance of landslides where Wasatch crops out. Across creek at Sunlight ski area the Wasatch-Mesaverde contact is in valley where ski area is located. Slopes on west (Wasatch) side of valley are very unstable, while east slopes (Mesaverde) are only moderately unstable. Main ski lift ends on knob capped by basaltic gravel that is surrounded by landslides. A linear swale bisecting the knob is interpreted as a sackungen feature produced by lateral spreading of the ridge crest.

END OF DAY TWO. RETURN TO MOTEL.

Day Three

0.0 Depart Silver Spruce motel with all gear. Turn right onto US Highway 6 & 24 (6th Street). Continue through stoplight at 6th Street and Mel-Ray Road. Turn right at Grand Avenue, passing over I-70 and Colorado River; continue through downtown Glenwood Springs.

1.6 Turn right at stoplight onto 23rd Street, turn right at 27th Street, and cross Roaring Fork River on Sunlight Bridge, following signs for Sunlight ski area. Just beyond the bridge 27th Street bends south and merges with Midland Avenue.

2.1 **STOP 1. Overview of upwarped pre-Bull Lake terrace.** Park on right shoulder immediately after 27th Street and Midland Avenue merge. Sharply tilted surface to south, which slopes away from valley axis towards valley wall, consists of deformed Eagle Valley Evaporite overlain by deformed pre-Bull Lake terrace gravel (Piety, 1981) and is capped by basalt-rich debris-flow and hyperconcentrated flood deposits that are locally mantled by loess. The riverside edge of this surface, which at one time must have sloped down to the east and north, is now upwarped away from the river, especially at its northern end. The upwarp may result from upward flowage (diapirism) of buried halite, gypsum, and anhydrite in the Eagle Valley Evaporite responding to differential loading which results from erosion of the valley by the river through time. Continue south on Midland.

3.5 Take right hand fork (Fourmile Road) at “Y” intersection.

4.8 **STOP 2. Upwarped debris-flow deposits.** Park on right shoulder in front of ranch house. Private land. Walk east across irrigated fields to edge of mesa. Irrigated fields underlain by loess that mantles debris-flow and terrace deposits. Note abundant, large basalt boulders on edges of the surface. Differential uplift of this surface is obvious from this perspective. Diapiric upwelling of halite, gypsum, and anhydrite is probably responsible for this deformation. Adjacent Pinedale terraces appear to be undeformed. Along west valley margin to south is a sharply upwarped early Bull Lake terrace which presently is undergoing residential development. Snails from a correlative terrace on the east side of the valley yielded amino acid ratios suggesting an age of 100,000±80,000 years BP (Piety, 1981). Out of view behind this terrace is a slightly lower, moderately upwarped, late Bull Lake terrace near Sievers Corner. Several nearby Pinedale terraces are slightly upwarped or are undeformed.

Note basalt flow on nose of ridge to northwest, which is the topographically lowest known remnant of the Sunlight volcanic sequence. Several basalt flows and an interbedded cobbly fluvial gravel which cap mesa to southeast are informally included in the Spring Valley volcanic sequence. Lowermost flow in this sequence has been submitted for 40Ar/39Ar dating. Continue south on Fourmile Road.

6.1 Turn left on Sunlight Road (CR 73).

6.3 **STOP 3. Overview of large slump-flow landslide.** Park on right shoulder at junction of Sunlight Road and Deer Park Road (CR 75). A tremendous slump-flow landslide heads in a 93 ha bowl of basalt-capped Mancos across Fourmile Creek. It funnels through a gap in the Dakota hogback and spreads out in a fan over the lower hillslope and valley floor of Fourmile Creek. Fan contains nearly 6,000,000 m^3 of debris, which is far less than the volume of bowl from which it is derived. In that the fan appears to be little eroded, this volume difference suggest material from the bowl either slid or was eroded from it prior to this landslide. Remains of a similar yet much older feature are preserved a short distance north, indicating prior landsliding at least in part was responsible for creation of the bowl. To the south Maroon Formation is complexly deformed by numerous folds and faults within the monocline. Retrace route back to Fourmile Road.

7.4 Turn left on Dry Park Road (CR 125) and follow strike valley in Maroon Formation. Ridge on right capped by Dakota Sandstone; slopes below are underlain by Morrison, Entrada, Chinle, and State Bridge Formations, which are mostly covered by colluvium.

9.5 **STOP 4. View secondary deformation within Grand Hogback Monocline.** Park near wire gate. Private land. Cross wire gate and walk to arroyo. Beds in Maroon dip about 55° southwest at arroyo head, but a short distance west are folded nearly horizontal by a faulted(?) monocline. Dips gradually steepen westward towards the Dakota Hogback, where they slightly exceed 50°.

9.9 Entering Dry Park. Note extensive hay fields irrigated with water from Fourmile Creek. Dakota Sandstone caps ridge on right; Maroon Formation underlies Dry Park and forms ridge to left. Great view of Mount Sopris to south.

10.8 Ranch headquarters. Bright red cliffs to left across Roaring Fork River are in Maroon Formation. Underlying tan and pinkish beds are Eagle Valley Formation. Basalt Mountain visible at skyline to left.

11.2 **STOP 5 & LUNCH. Regional overview from Dakota hogback ridge.** Park on shoulder opposite wooden gate next to wooden corrals. Private land. Walk up dirt road to crest of Dakota Hogback. Bring lunch along and take your trash back with you. An irrigation pipeline bringing water from Fourmile Creek into Dry Park underlies the excavated cut. Dakota and Morrison are exposed in cut. On north side of cut note slump block in Dakota and associated folding, which may have resulted when ancestral Fourmile Creek undercut the Dakota dip slope and caused a block of sandstone to slide down the dip slope. Uppermost Morrison beds are brightly colored, perhaps due to weathering prior to deposition of the Dakota. Good views to west of faulted late Tertiary/early Quaternary basaltic gravels which cap the mesas. To north the increased displacement on these faults in basalt flows near Threemile Creek is obvious. Abundant landslides and debris flows in Mancos strike valley.

To northeast basalt flow east of Lookout Mountain was dated at 10.1±0.5 Ma, whereas a basalt flow near Cottonwood Pass gave an age of 11.1±1.0 Ma (whole rock K-Ar ages in Larson and others, 1975). Mesa to left of Cottonwood Pass is Docks Flats, which is capped by a thick sequence of basalt flows; a middle flow from Dock Flats is currently being dated using the $^{40}Ar/^{39}Ar$ method. Trachyandesite in eruptive center at Little Buck Point below Dock Flats yielded an $^{40}Ar/^{39}Ar$ age of only 3.94±0.02 Ma on a sanidine crystal (Kirkham and others, 1995b). Large topographic depression between mesa on east side of Roaring Fork River and hill which climbs up to Dock Flats is Spring Valley. Note large landslide complex on northeast side of Spring Valley. A whole rock $^{40}Ar/^{39}Ar$ age of 22.4±0.3 Ma was obtained on a basalt flow at north end of Spring Valley that is only 320 m above the Roaring Fork River (Kirkham and others, 1995a). White River Uplift forms skyline to north. Continue south on Dry Park Road, following Maroon strike valley.

12.8 Turn left on Edgerton Creek Road (CR 108). Note basalt boulders in surficial deposits along Edgerton Creek.

13.9 Outcrops of Eagle Valley Formation on both sides of creek are locally overturned within small fault blocks.

14.4 Crystal River Ranch headquarters. Descending Edgerton Creek debris fan. Note basalt boulders. Good view of cliff at 11 o'clock with Maroon redbeds overlying pinkish and tan rocks of Eagle Valley Evaporite. Note basalt flow and associated late Tertiary sediments that cap the cliff.

15.0 Excellent view in middle distance to left of a diapir of Eagle Valley Evaporite piercing overlying Maroon Formation along the Roaring Fork Valley near the mouth of Cattle Creek. White River Uplift at skyline to left.

15.5 **STOP 6. View of evaporite deformation and folded Bull Lake terrace deposits.** Park on right shoulder at roadcut. Spectacular folding and faulting in Eagle Valley Evaporite in cliffs on south side of creek. At upper end of roadcut deformed evaporitic rocks are overlain by a thin veneer of Bull Lake age Roaring Fork River gravel, which in turn is overlain by basalt-rich gravel deposited by Edgerton Creek. Eastward, bedrock is in near vertical contact with Bull Lake terrace gravels. Contact may be an unconformity or a fault. East of this contact the gravels dip gently east until being anticlinally folded by an intrusive body of gypsum exposed at road level. Relationships between anticline and basaltic gravels at top of exposure are not clear. Continue east.

15.8 Cross Crystal River. Rocky Mountain School on left.

16.4 Entering Carbondale. Note Quaternary terraces, probably of Pinedale age.

16.7 Turn left at stoplight onto Highway 133.

17.8 Turn left (north) at stoplight onto Highway 82. Colluvium derived from the Maroon Formation is in roadcut on right. Pinedale terraces to left across Roaring Fork River do not appear to be deformed. Bull Lake terrace, which is slightly higher than the highway, is upwarped on its eastern edge. Several sinkholes are in Bull Lake terrace gravels, and a very large (3 x 7 x 17 m deep) void in Eagle Valley Evaporite on slope below terrace has caused leakage from the adjacent irrigation ditch and erosion of the nearby county road.

19.8 Contact between piercing evaporitic diapir and Maroon Formation in hills on right. Evaporitic rocks locally capped by pre-Bull Lake gravels.

21.6 Cross Cattle Creek. Hills across river are part of diapiric intrusion. Note that Pinedale terraces are slightly upwarped at river's edge, but not further back from terrace edge.

21.7 Turn right on Cattle Creek Road (CR 113), then turn right onto dirt frontage road between highway and Funland Park.

22.0 **STOP 7. Outcrops of gypsum.** Turn left into parking area and walk to roadcut in evaporitic rocks. Thick bed of gypsum within diapir exposed in cut. Note abundant voids within formation, including one that has been filled with surficial materials that washed or fell into it. Retrace route to Highway 82.

22.3 Turn right onto Highway 82. Note Pinedale terraces along Roaring Fork River on left; several are slightly upwarped adjacent to river.

23.4 Turn right at stoplight on Colorado Mountain College Road (CR 114). Road approximately follows northern boundary of diapir.

24.1 Roadcuts on left in weathered basalt, whose permeabilities probably were increased by fracturing related to diapiric activity.

24.3 Roadcuts for next 1.1 km expose deformed evaporitic rocks, including massive gypsum beds.

25.3 Basalt flow in roadcut on left is part of Spring Valley volcanic sequence.

26.2 Colorado Mountain College campus on right.

26.8 **STOP 8. Overview of Spring Valley sag.** Park on shoulder. Anomalous, crescent-shaped Spring Valley is about 7 km long, averages about 0.9 km wide, and has a very flat floor which drains north into Red Canyon. According to long-time resident C. Cox (1994, oral commun.) during the late 1800's Spring Valley was a closed depression and a lake covered much of the valley floor until a ditch was hand dug by his ancestors at the north end of the valley to drain the lake and initiate agricultural use of the land for homesteading purposes. Title to the land was transferred from the federal government in 1896, therefore the lake was drained prior to this date. The drain ditch still serves as the outlet to Red Canyon. A sample of medium gray lacustrine clay collected from a hole dug into the valley floor has been submitted for ^{14}C dating.

Hills east and northeast of Spring Valley are part of a huge landslide complex involving gently dipping Maroon bedrock and overlying subhorizontal basalt flows. The basalt cap west of the valley is shattered by faults and deformed by synclinal sags. Spring Valley is parallel to the warped terraces found in the Roaring Fork Valley between Glenwood and Carbondale. In that mainstem fluvial gravels have not been found in or adjacent to the Spring Valley, it is unlikely that it was carved by an ancestral Roaring Fork River. The valley is a crescent-shaped half graben into which Maroon Formation and overlying late Tertiary basalts have been downdropped. In view of the historical lake in the valley, the most recent deformation may have been latest Holocene.

Spring Valley may owe its origin to regional extension, but its shape is unlike any other Neogene graben in Colorado, and it does not fit well with regional structures. The valley probably is a large collapse feature or sag produced by the evacuation of evaporitic rocks from beneath it. We theorize that as the nearby Roaring Fork River downcut into the Maroon and underlying evaporitic rocks, differential loading caused a thick, ductile mass of halite, gypsum, and anhydrite beneath Spring Valley to flow towards the river. Beneath Roaring Fork Valley these low density rocks rose diapirically, increasing structural closure on Cattle Creek Anticline and warping Quaternary terraces. Location and timing of deformed terraces suggest that at least two diapirs resulted from this process. The floor of Spring Valley sagged as evaporitic rocks flowed from beneath it, creating a closed basin in which a lake developed. A large landslide complex east of the valley failed along bedding planes in the Maroon as lateral support was removed by the sagging valley floor. As evaporitic rocks flowed beneath the basalt cap west of the valley, the cap was jostled about, shattered by faults, and deformed by synclinal sags. Continue east on Colorado Mountain College Road (CR 114).

27.4 Rivendell sod farm on left.

28.5 Turn left on Red Canyon Road (CR 115). Hills on both sides of road for next 2 km consist of eroded landslide deposits.

29.1 Skyline to left formed by Sunlight Peak. Mesa sloping east from Sunlight Peak is a faulted dip slope underlain by volcanic rocks. Outcrop of Maroon Formation on right is either a toreva block within the landslide complex or island of bedrock extending up through it.

30.9 Road climbs up over an older debris-flow fan. Good view of shattered basalt cap on left across Spring Valley.

31.5 **STOP 9. View early Miocene basalt and hand-dug drainage ditch by which Spring Valley was dewatered.** Park on right between compartmental mail boxes and dumpsters and walk to roadcut. Coarse-grained basalt exposed in roadcut has a whole rock $^{40}Ar/^{39}Ar$ age of 22.4±0.3 Ma (Kirkham and others, 1995a). Note ditch behind house to south that drains Spring Valley into Red Canyon. Good view of faulted basalt cap to south. To northeast bedrock generally dips southwestward in the south flank of the White River Uplift. Continue northwest on Red Canyon road (CR 115).

32.0 Graben on right contains basalt that is faulted against Maroon Formation on both sides of valley.

33.4 Use extreme caution while traversing this dangerous shelf road. Note young geomorphic character of this steep-walled canyon, which may be related to subsidence of Spring Valley. Cross approximate axis of Glenwood Springs Syncline, which separates south flank of White River Uplift from Cattle Creek Anticline.

34.0 **STOP 10. Overview of Glenwood Springs Syncline.** Park on outside shoulder of switchback. Note gentle dips in Maroon beds within the Glenwood Springs Syncline to north that abruptly steepen as they approach the Cattle Creek Anticline. Good view of upwarped surface at mouth of Fourmile Creek to west across valley.

END OF FIELD TRIP. RETURN TO DENVER.

REFERENCES

Aleinikoff, J.N., Reed, J.C., Jr., and DeWitt, Ed, 1993, The Mount Evans Batholith in the Colorado Front Range: Revision of its age and reinterpretation of its structure: Geological Society of America Bulletin v. 105, p. 791–806.

Anderson, J.L., 1983, Proterozoic anorogenic plutonism in North America,in Medaris, L.G., and others, eds., Proterozoic geology: Geological Society of America Memoir 161, p. 133–154.

Anderson, J.L., and Thomas, W.M., 1985, Proterozoic anorogenic two-mica granites: Silver Plume and St. Vrain batholiths of Colorado: Geology, v. 13, p. 177–180.

Barker, Fred, Hedge, C.E., Millard, H.T., and O’Neil, J.R., 1976, Pikes Peak Batholith: geochemistry of some minor elements and isotopes, and implications for magma genesis, *in* Epis, R.S., and Weimer, R.J., eds., Studies in Colorado field geology: Colorado School of Mines Professional Contributions 8, p. 44–56.

Barrett, J.K., and Pearl, R.H., 1976, Hydrogeological data of thermal springs and wells in Colorado: Colorado Geological Survey Information Series 6, 124 p.

_____1978, An appraisal of Colorado’s geothermal resources: Colorado Geological Survey Bulletin 39, 224 p.

Bass, N.W., and Northrup, S.A., 1950, South Canyon Dolomite Member, a unit of Phosphoria age in Maroon Formation near Glenwood Springs, Colorado: American Association of Petroleum Geologists Bulletin, v. 34, no. 7, p. 1540–1551.

_____1963, Geology of the Glenwood Springs quadrangle and vicinity, northwestern Colorado: U.S. Geological Survey Bulletin 1142-J, 74 p.

Bookstrom, A.A., 1988, The Silver Plume-Georgetown district, in Reed, J.C., Jr., Bryant, Bruce, Sims, P.K., Beaty, D.W., Bookstrom, A.A., Grose, T.L.T., Mallory, W.W., Wallace, S.R., and Thompson, T. B., Geology and mineral resources of central Colorado, *in* Holden, G.S., ed., Geological Society of America 1888-1988, Centennial Meeting, Denver, Colorado, Field Trip Guidebook: Colorado School of Mines Professional Contributions 12, p. 85-90.

Boreck, D.L., and Murray, D.K., 1979, Colorado coal reserve depletion data and coal mine summaries: Colorado Geological Survey Open-File Report 79-1.

Bowen, Tim, 1988, Engineering geology of Glenwood Canyon, *in* Holden, G.S., ed., Geological Society of America 1888-1988, Centennial Meeting, Denver, Colorado, Field Trip Guidebook: Colorado School of Mines Professional Contributions 12, p. 408–418.

Braddock, W.A., and Cole, J.C., 1979, Precambrian structural relations, metamorphic grade, and intrusive rocks along the northeast flank of the Front Range, Colorado, *in* Ethridge, F.G., ed., Field guide to the northern Front Range and northwest Denver basin, Colorado: Department of Earth Sciences, Colorado State University, Fort Collins, p. 105–121.

Brewer, J.A., Allmendinger, R.W., Brown, L.D., Oliver, J.E., and Kaufman, S., 1982, COCORP profiling across the Rocky Mountain front in southern Wyoming, Part 1, Laramide structure: Geological Society of America Bulletin, v. 93, p. 1242–1252.

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

Bryant, Bruce, and Naeser, C.W., 1980, The significance of fission-track ages of apatite in relation to the tectonic history of the Front and Sawatch Ranges: Geological Society of America Bulletin, v. 91, pt. 1, p. 156–164.

Bryant, Bruce, and Beaty, D.W., eds., Mineral deposits and geology of central Colorado in International Geological Congress. 28th, Washington, D.C., 1989, Field Trip Guidebook T129: Washington, D.C., American Geophysical Union, 73 p.

Cannon, S.H., Powers, P.S., Pihl, R.A., and Rogers, W.P., 1995, A preliminary evaluation of the fire-related debris flows on Storm King Mountain, Glenwood Springs, Colorado: U.S. Geological Survey Open-file Report 95-508, 38 p.

Carroll, C.J., Kirkham, R.M., and Stelling, P.L., 1996, Geologic map of the Center Mountain quadrangle, Garfield County, Colorado: Colorado Geological Survey Open-file Report 96-2, scale 1:24,000.

Chapin, C.E., and Cather, S.M., 1981, Eocene tectonism and sedimentation in the Colorado Plateau-Rocky Mountain area: Arizona Geological Digest, v. 14, p. 175–198.

Collins, B.A., 1976, Coal deposits of the Carbondale, Grand Hogback, and southern Danforth Hills coal fields, eastern Piceance Basin, Colorado: Colorado School of Mines Quarterly, v. 71, no. 1, 138 p.

Cross, T.A., 1986, Tectonic controls of foreland basin subsidence and Laramide style deformation, western United States, *in* Allen, P.A., ed., Foreland basins: International Association of Sedimentologists Special Publication 8, p. 15–39.

DeVoto, R.H., Bartleson, B.L., Schenk, C.J., and Wachter, N.B., 1986, Late Paleozoic stratigraphy and syndepositional tectonism, northwestern Colorado, *in* Stone, D.S., ed., New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists, Denver, Colorado, p. 37–49.

Dickson, P.A., Kewer, R.P., and Wright, J.E., 1986, Regional fault study: central Front Range, Colorado, *in* Rogers, W.P., and Kirkham, R.M., eds., Contributions to Colorado seismicity and tectonics-A 1986 update: Colorado Geological Survey Special Publication 28, p. 172–185.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.V., Lundin, E.R., McKiltrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America Bulletin, v. 100, p. 1023–1039.

Eaton, G.P., 1986, A tectonic redefinition of the southern Rocky Mountains: Tectonophysics, v. 132, p. 163–193.

Epis, R.C., and Chapin, C.E., 1975, Geomorphic and tectonic implications of the post-Laramide, late Eocene erosion surface in the Southern Rocky Mountains, *in* Curtis, B.F., ed., Cenozoic geology of the Southern Rocky Mountains: Geological Society of America Memoir 144, p. 45–74.

Fairer, G.M., Green, M.W., and Shroba, R.R., 1993, Preliminary geologic map of the Storm King Mountain quadrangle, Garfield County, Colorado: U.S. Geological Survey Open-file Report 93-320, 23 p., 1 pl., scale 1:24,000.

Freeman, V.L., 1971, Permian deformation in the Eagle Basin, Colorado, *in* Geological Survey Research 1971: U.S. Geological Survey Professional Paper 750-D, p. D80–D83.

Giegengack, R.F., Jr., 1962, Recent volcanism near

Dotsero, Colorado: University of Colorado, M.S. thesis, 43 p.

Goter, S.K., Presgrave, B.W., Henrisey, R.F., and Langer, C.J., 1988, The Carbondale, Colorado, earthquake swarm of April-May, 1984: U.S. Geological Survey Open-file Report 88-417, 16 p.

Graubard, C.M., and Mattinson, J.M., 1990. Syntectonic emplacement of the ~1440 Ma Mt. Evans pluton and history of motion along the Idaho Springs-Ralston Shear Zone, central Front Range, Colorado [abs]: Geological Society of America Abstrasts with Programs, v. 22, no. 6, p. 12.

Green, M.W., Fairer, G.M., and Shroba, R.R., 1993, Preliminary geologic map of the New Castle quadrangle, Garfield County, Colorado: U.S. Geological Survey Open-file Report 93-310, 33 p., 1 pl., scale 1:24,000.

Gregory, K.M., 1994, Paleoclimate and paleoelevation of the Florissant flora, *in* Evanoff, Emmett, ed., Late Paleocene geology and paleoenvironments of central Colorado with emphasis on the geology and paleontology of Florissant Fossil Beds National Monument: Guidebook for field trip Rocky Mountain Section of the Geological Society of America at Durango Colorado, p. 57–66.

Gregory, K.M., and Chase, C.G., 1992, Tectonic significance of paleobotanically estimated climate of the late Eocene erosion surface, Colorado: Geology, v. 20, p. 581-585.

Gries, R.R., 1983, North-south compression of the Rocky Mountain foreland structures, in Lowell, J.D., and Gries, R.R., eds., Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists, Denver, Colorado, p. 9–32.

Grout, M.A., Abrams, G.A., Tang, R.L., Hainsworth, T.J., and Verbeek, E.R., 1991, late Laramide thrust-related and evaporite-domed anticlines in the southern Piceance basin, northwestern Colorado: American Association of Petroleum Geologists Bulletin, v. 75, no. 2, p. 205-218.

Hamilton, Warren, 1978, Mesozoic tectonics of the western United States, in Howell, D.G. and McDougal, K.A., eds., Mesozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium, p. 33-70.

_____1988, Laramide crustal shortening, in Perry, W.J., and Schmidt, C.J., eds., Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 27–39.

Hawley, C.C., and Moore, F.B., 1967, Geology and ore deposits of the Lawson-Dumont-Fall River district, Clear Creek County, Colorado: U.S. Geolo–gical Survey Bulletin 1231, 92 p.

Hunt, C.B., 1969, Geologic history of the Colorado River: U.S. Geological Survey Professional Paper 660-C, p. C59–C130.

Izett, G.A., and Wilcox, R.E., 1982, Map showing localities and inferred distribution of the Huckleberry Ridge, Mesa Falls, and Lava Creek ash beds (Pearlette family of ash beds) of Pliocene and Pleistocene age in the western United States and southern Canada: U.S. Geological Survey Miscellaneous Investigations Map I-1325, scale 1:4,000,000.

Johnson, R.C., and May, Fred, 1980, A study of the Cretaceous-Tertiary unconformity in the Piceance Basin, Colorado: The underlying Ohio Creek Formation (Upper Cretaceous) redefined as a member of the Hunter Canyon or Mesaverde Formation: U.S. Geological Survey Bulletin 1482-B, 27 p.

Johnson, S.Y., Schenk, C.J., Anders, D.L., and Tuttle, M.L., 1990, Sedimentology and petroleum occurrence, Schoolhouse Member, Maroon Formation (Lower Permian), northwestern Colorado: American Association of Petroleum Geologists Bulletin v. 74, no. 2, p. 135–150.

Johnson, S.Y., Schenk, C.J., and Karachewski, J.A., 1988, Pennsylvanian and Permian depositional systems in the Eagle Basin, northwest Colorado, *in* Holden, G.S., ed., Geological Society of America 1888-1988 Centennial Meeting Field Trip Guidebook: Colorado School of Mines Professional Contributions 12, p. 156–175.

Kirkham, R.M., Cannon, S.H., and Powers, P.S., 1996, Geology of the South Canyon fire area, south flank of Storm King Mountain, Garfield County, Colorado: Colorado Geological Survey Information Series (in preparation)

Kirkham, R.M., Streufert, R.K., and Cappa, J.A., 1995a, Geologic map of the Glenwood Springs quadrangle, Garfield County, Colorado: Colorado Geological Survey Open-file Report 95-3, 22 p., 1 pl., scale 1:24,000.

_____1995b, Geologic map of the Shoshone quadrangle, Garfield County, Colorado: Colorado Geological Survey Open-file Report 95-4, 16 p., 1 pl., scale 1:24,000.

Kirkham, R.M., Streufert, R.K, Hemborg, H.T., and Stelling, P.L., 1996, Geologic map of the Cattle Creek quadrangle, Garfield County, Colorado: Colorado Geological Survey Open-file Report 96-1, scale 1:24,000.

Kluth, C.F., 1986, Plate tectonics of the Ancestral Rocky Mountains, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 353–369.

Larson, E.E., Ozima, Minouro, and Bradley, W.C., 1975, Late Cenozoic basic volcanism in northwestern Colorado and its implications concerning tectonism and the origin of the Colorado River system, *in* Curtis, B.F., ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 155, p. 155–178.

Lincoln-Devore Testing Laboratory, 1978, Geologic hazards of the Glenwood Springs metropolitan area, Garfield County, Colorado: Colorado Geological Survey Open-file Report 78-10, 27 p.

Lovering, T.S., and Mallory, W.W., 1962, The Eagle Valley Evaporite and its relation to the Minturn and Maroon Formation, northwest Colorado, *in* Geological Survey Research 1962: U.S. Geological Survey Professional Paper 450-D, p. D45-D48.

Madole, R.F., 1991, Colorado Piedmont section, *in* Morrison, R.B., ed., Quaternary nonglacial geology: conterminous U.S.: Geological Society of America, The Geology of North America, v. K-2, p. 456–462.

Mallory, W.W., 1960, Outline of Pennsylvanian stratigraphy of Colorado, *in* Weimer, R.J., and Haun, J.D., eds., Guide to the geology of Colorado: Geological Society of America, Rocky Mountain Association of Geologists, and Colorado Scientific Society, p. 23–33.

_____1966, Cattle Creek Anticline, a salt diapir near Glenwood Springs, Colorado, in Geological Survey Research 1966: U.S. Geological Survey Professional Paper 550-B, p. B12–B15.

_____1971, The Eagle Valley Evaporite, northwest Colorado-a regional synthesis: U.S. Geological Survey Bulletin 1311-E, p. E1–E37.

Mears, A.I., 1977, Debris-flow analysis and mitigation-An example from Glenwood Springs, Colorado: Colorado Geological Survey Information Series 8, 45 p.

Murray, F.N., 1966, Stratigraphy and structural geology of the Grand Hogback Monocline, Colorado: University of Colorado, Ph.D. thesis, 219 p.

_____1969, Flexural slip as indicated by faulted lava flows along the Grand Hogback Monocline, Colorado: Journal of Geology, v. 77, p. 333-339.

Perry, W.J., Jr., Grout, M.A., Hainsworth, T.J., and Tang, R.L., 1988, Wedge model for late Laramide basement-involved thrusting, Grand Hogback Monocline and White River Uplift, western Colorado [abs.]: Geological Society of America Abstracts with Program, v. 20, no. 7, p. 384–385.

Piety, L.A., 1981, Relative dating of terrace deposits and tills in the Roaring Fork Valley, Colorado: University of Colorado, M.S. thesis, 209 p.

Pierce, K.L., 1979, History and dynamics of glaciation in the northern Yellowstone National Park area: U.S. Geological Survey Professional Paper 729-F, 90 p.

Reed, J.C., Jr, 1988, Precambrian rocks in Tenmile Canyon, *in* Reed, J.C., Jr., Bryant, Bruce, Simms, P.K., Beaty, D.W., Bookstrom, A.A., Grose, T.L.T., Mallory, W.W., Wallace, S.R., and Thompson,T.B., 1988, Geology and Mineral Resources of central Colorado, in Holden, G.S., ed., Geological Society of America 1888-1988 Centennial Meeting Filed Trip Guidebook: Colorado School of Mines Professional Contributions 12, p. 92–93.

Reed, J.C., Jr., Bickford, M.E., Premo, W.R., Aleinikoff, J.N., and Pallister, J.S., 1987, Evolution of the Early Proterozoic Colorado province: Geology, v. 15, no, 9, p. 861–865.

Reed, J.C., Jr., Bryant, Bruce, Sims, P.K., Beaty, D.W., Bookstrom, A.A., Grose, T.L.T., Mallory, W.W., Wallace, S.R., and Thompson, T.B., 1988, Geology and mineral resources of central Colorado, *in* Holden, G.S., ed., Geological Society of America 1888-1988 Centennial Meeting, Denver, Colorado: Colorado School of Mines Professional Contributions 12, p. 68–121.

Richmond, G.M., 1986, Stratigraphy and correlation of glacial deposits of the Rocky Mountains, the Colorado Plateau, and the ranges of the Great Basin, *in* Sibrava, V., Bowen, D.Q., and Richmond, G.M., eds., Quaternary glaciations in the northern hemisphere: Quaternary Science Reviews, v. 5, p. 99–127.

Robinson, C.S., Gallant, W.A., and Cochran, D.M., 1976, Land use and engineering geology of the Front Range, Colorado, in Epis, R.C., and Weimer, R.J., eds., Studies in Colorado field geology: Colorado School of Mines Professional Contributions no. 8, p. 486–504.

Robinson, C.S., Warner, L.A., and Wahlstrom, E.E., 1974, General geology of the Harold D. Roberts tunnel, Colorado: U. S. Geological Survey Professional Paper 831-B, 48 p.

Rushworth, P., Haefner, B.D., Hynes, J.L., and Streufert, R.K., 1989, Reconnaissance study of coal fires in inactive Colorado coal mines: Colorado Geological Survey Information Series 26, 60 p.

Schenk, C.J., 1992, Stratigraphic correlations between the Eagle Valley Evaporite and Minturn Formation, Eagle Basin, northwest Colorado: U.S. Geological Survey Bulletin 1787-GG, 8 p.

Scott, G. R., 1972, Geologic map of the Morrison quadrangle, Jefferson County, Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-790-A, scale 1:24,000.

_____1975, Cenozoic surfaces and deposits in the southern Rocky Mountains, in Curtis, B.F., ed., Cenozoic history of the southern Rocky Mountains:

Geological Society of America Memoir 144, p. 227–248.
Selverstone, Jane, Hodgins, Meghan, and Shaw, Colin, 1995, 1.4 Ga versus 1.7 Ga metamorphism in the northern Colorado Front Range: a repeated history of post-accretion midcrustal heating [abs.]: Geological Society of America Abstracts with Programs, V. 27, no. 6, p. A-49.
Shaw, C.A., Snee, L.W., and Reed, J.C., Jr., 1995, $^{40}Ar/^{39}Ar$ data identify transient~1.4 Ga thermal event related to mid-Proterozoic metamorphism in the Colorado Front Range [abs.]: Geological Society of America Abstracts with Programs, v. 27, no. 6, p. A-50.
Shroba, R.R., 1994, Quaternary loess stratigraphy along the Colorado River between Glenwood Springs and Rifle, Colorado—preliminary findings [abs.]: American Quaternary Association, Biennial Meeting, 13th, Minneapolis, Minn., Program and Abstracts, p. 246.
Shroba, R.R., Fairer, G.M., and Green, M.W., 1994, Preliminary geologic map of the Silt quadrangle, Garfield County, Colorado: U.S. Geological Survey Open-file Report 94-696, 24 p., 1 pl., scale 1:24,000.
Shroba, R.R., Green, M.W., and Fairer, G.M., 1995, Pre–liminary geologic map of the Rifle quadrangle, Garfield County, Colorado: U.S. Geological Survey Open-file Report 95-52, 22 p., 1 pl., scale 1:24,000.
Sims, P.K., 1989, Central City and Idaho Springs districts, Front Range, Colorado, *in* Bryant, Bruce and Beaty, D.W., eds., Mineral deposits and geology of central Colorado, Field Trip Guidebook T129: Washington, D.C., American Geophysical Union, p. 15–18.
Smithson, S.B., Brewer, J.A., Kaufman, S., Oliver, J.E., and Hurich, C.A., 1979, Structure of the Laramide Wind River Uplift, Wyoming, from COCORP deep reflection data and from gravity data: Journal of Geophysical Research, v. 84, p. n5955–5972.
Soule, J.M., 1988, Landslides in the vicinity of Dowds Junction, Vail-Minturn area near the junction of U.S. Highway 24 and Interstate 70, Eagle County, Colorado, in Holden, G.S., ed., Geological Society of America 1888-1988 Centennial Meeting Field Trip Guidebook: Colorado School of Mines Professional Contributions 12, p. 402–407.
_____, 1992, Precambrian to earliest Mississippian stratigraphy, geologic history, and paleography of northwestern and west-central Colorado: U.S. Geological Survey Bulleetin 1787-U, 35 p.
Soule, J.M., and Stover, B.K., 1985, Surficial geology, geomorphology, and general engineering geology of parts of the Colorado River valley, Roaring Fork Valley, and adjacent areas, Garfield County, Colorado: Colorado Geological Survey Open-file Report 85-1.
Steven, T.A., Hon, K., and Lanphere, M.A., 1995, Neogene geomorphic evolution of the central San Juan Mountains near Creede, Colorado: U.S. Geological Survey Misc. Investigations Map I-2504.
Stewart, J.H., Poole, F.G., and Wilson, R.F., 1972, Stratigraphy and origin of the Triassic Moenkopi Formation and related strata in the Colorado Plateau region: U.S. Geological Survey Professional Paper 691, 195 p.
Stover, B.K., 1986, Geologic evidence of Quaternary faulting near Carbondale, Colorado, with possible associations to the 1984 Carbondale earthquake swarm *in* Rogers, W.P, and Kirkham, R.M., eds., Contributions to Colorado seismicity and tectonics-A 1986 update: Colorado Geological Survey Special Publication 28, p. 295–301.
_____1988, Booth Creek rockfall hazard area, in Holden, G.S., ed., Geological Society of America 1888-1988 Centennial Meeting Field Trip Guidebook: Colorado School of Mines Professional Contributions 12, p. 395–401.
_____1993, Debris-flow origin of high-level sloping surfaces on the northern flanks of Battlement Mesa, and surficial geology of parts of North Mamm Peak, Rifle, and Rulison quadrangles, Garfield County, Colorado: Colorado Geological Survey Bulletin 50, 34 p.
Streckeisen, A., 1973, Plutonic-rock classification and nomenclature recommended by the IUGS subcommission on the systematics of igneous rocks: Geotimes, v. 10, p. 26–31.
Streufert, R.K., and Kirkham, R.M., 1996, Preliminary geologic map of the north half of the Cottonwood Pass quadrangle, Eagle and Garfield Counties, Colorado: Colorado Geological Survey Open-file Report 96-3, scale 1:24,000 (in preparation).
Tweto, Ogden, 1975, Laramide (Late Cretaceous-early Tertiary) orogeny in the Southern Rocky Mountains, in Curtis, B.F., ed., Cenozoic history of the Southern Rocky Mountains: Geological Society of America Memoir 144, p. 1-44.
_____1977, Tectonic history of west-central Colorado, in Veal, H.K., ed., Exploration frontiers of the central and southern Rockies: Rocky Mountain Association of Geologists, Denver, p. 11–22.
_____1978, Northern rift zone guide 1, Denver-Alamosa, Colorado, in Hawley, J.W., compiler, Guidebook to the Rio Grande Rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 13–32.
_____1979a, The Rio Grande Rift system in Colorado, *in* Rieker, R.E., ed., Rio Grande rift: tectonics and

magmatism: American Geophysical Union, Washington, D.C., p. 33–56.

_____1979b, Geologic map of Colorado: U.S. Geological Survey, scale 1:500,000.

_____1987, Rock units in the Precambrian basement in Colorado: U.S. Geological Survey Professional Paper 1321, 54 p.

Tweto, Ogden, and Lovering, T.S., 1977, Geology of the Minturn 15-minute quadrangle, Eagle and Summit Counties, Colorado: U.S. Geological Survey Professional Paper 956, 96 p.

Tweto, Ogden, Moench, R.H., and Reed, J.C., Jr., 1978, Geologic map of the Leadville 1 x 2 degree quadrangle, northwest Colorado: U.S. Geological Survey Misc. Investigations map I-999.

Tweto, Ogden, and Sims, P.K., 1963, Precambrian ancestry of the Colorado mineral belt: Geological Society of America Bulletin, v. 74, p. 991–1014.

Unruh, D.M., Snee, L.W., and Ford, E.E., 1995, Age and cooling history of the Pikes Peak Batholith and associated pegmatites [abs.]: Geological Society of America Abstracts with Programs, v. 27, no. 6, p. 468.

Unruh, J.R., Wong, I.G., Bott, J.D.J., Silva, W.J., and Lettis, W.R., 1993, Seismotectonic evaluation, Rifle Gap Dam, Silt Project, Ruedi Dam, Frying Pan-Arkansas Project, northwestern Colorado: unpublished report prepared for the U.S. Bureau of Reclamation, Denver, Colorado by William Lettis & Associates and Woodward-Clyde Consultants, Oakland, California, 154 p.

Warner, L.A., 1978, The Colorado Lineament: a Middle Proterozoic wrench fault system: Geological Society of America Bulletin v. 87, p. 161–171.

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