Guidebook to

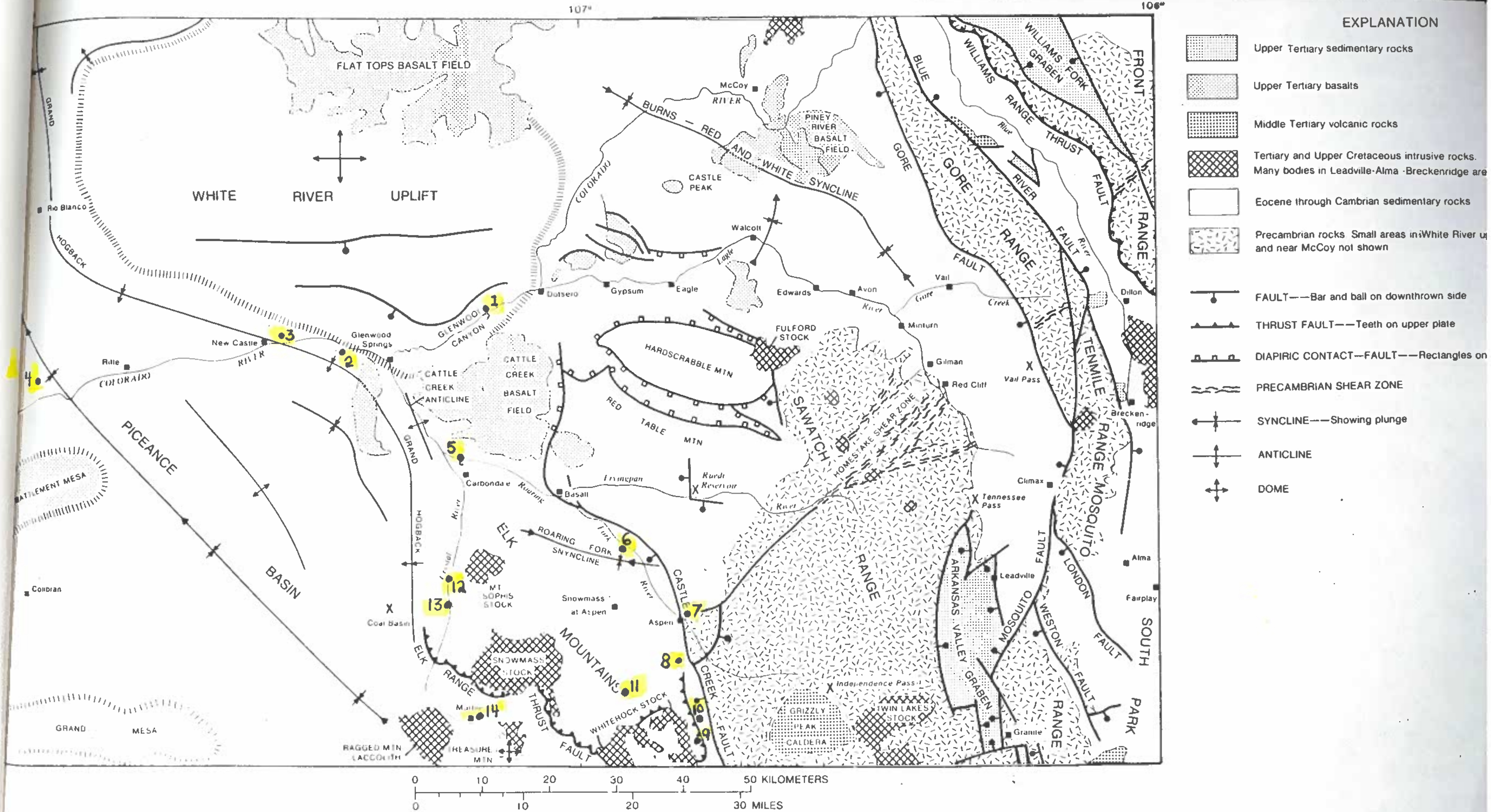
Geology of West-Central

Colorado

Centennial Fall Field Trip
Colorado Scientific Society
1982

Compiled by

Bruce Bryant



(TWETO) PLATE 1--PRINCIPAL GEOGRAPHIC AND TECTONIC FEATURES IN WEST-CENTRAL COLORADO - Stops labelled

CONTENTS

Glenwood Canyon thought to be a Neogene feature
Grand Hogback is post-middle Eocene

Road Log for Colorado Scientific
Society Centennial Fall Field Trip
October, 1-3, 1982

These logs are rearranged and modified from Young and others (1981) and Freeman and Bryant (1977). The trip route is shown on accompanying fold-out map. For Friday, October 1, the trip begins at Exit 133 at Dotsero in Pennsylvanian rocks of the Eagle Basin, passes through the White River uplift in Glenwood Canyon, which exposes lower Paleozoic and Proterozoic rocks, and then crosses the Grand Hogback into lower Tertiary rocks of the Piceance Basin.

From last stop	Total	
0	0	Exit 133, Dotsero C14 date on basalt of 4000 y bp 1/4 m E exit to Dotsero
.6	.6	On north side of highway distorted gypsum beds of Eagle Valley Formation cap low hills on steeply dipping south flank of Dotsero anticline, whose crest lies about 1 km north of highway.
.3	.9	Railroad cuts south of river exposes dark gray shale and thin limestone in Belden Formation.
1.6	2.5	Belden Formation north of highway.
.7	3.2	Warm springs on both sides of Colorado River. Low ridge of travertine shows in bottomland across river. Large volume of salt from Eagle Valley evaporites enter the river at this point. Road cut on northwest side of highway exposes top of Leadville Limestone, a few meters of varicolored shale of Molas Formation and thin beds of gray limestone at base of Belden Formation.
.1	3.3	Hills north of highway and south of river formed by Belden Formation.
.2	3.5	Enter Glenwood Canyon, cut through the White River uplift, which is a domal upwarp over 5200 km^2 in area. It is capped by Paleozoic sediments (commonly Leadville Limestone of Mississippian age).
		Volcanic extrusives of late Cenozoic age cover the northeastern part of the uplift and support the highest area of the White River Plateau, the Flattops Wilderness area not visible here. The uplift is bounded on the north by a series of lesser folds including those of the Axial Basin anticline. Bordering the uplift on the east is the Eagle River Basin, a southeastward projecting tongue of the Sand Wash Basin, and on the west is the Piceance Creek Basin.

From last stop	Total	
		Dips on the east and north sides are relatively gentle; but on the west and southwest sides, along the Grand Hogback, the beds approach the vertical and in some places are somewhat overturned. Westward thrusting has been reported at depth along the Hogback, and large normal faults are common along the south flank near Glenwood Springs. Some uplift of this structure occurred in the Paleocene, but the major movement began in early-middle Eocene to produce the last of the Laramide mountains in the Colorado West.
.3	3.8	Road cut in Broken Rib Member of Dyer Formation.
.1	3.9	Green shale overlain by black shale and in turn by light tan quartzite in Parting Formation.
.1	4.0	Garfield County line. Contact between Manitou and Parting Formations.
.1	4.1	Cliff or Manitou Formation next to road.
.3	4.4	Note prominent joints in Manitou Formation, north side of road.
.3	4.7	Road cut in Sawatch Quartzite, which makes main cliff above highway. Scrub junipers above Sawatch mark position of Dotsero Formation. Top brown cliffs formed by Manitou Formation.
.3	5.0	The notch in cliff above railroad tracks across the river is formed by 23-m thick glauconitic dolomite in Sawatch Formation.
.1	5.1	Sawatch Quartzite here slightly rose colored which is an unusual development. Note strongly developed northeast and northwest joint systems and prominent alteration along joints.
.6	5.7	Tie Gulch, Cliff east of gulch formed by Tie Gulch Member.
.3	6.0	Belden Formation (Pennsylvanian) exposed in graben in hills north of road and in big hills south of river.
.3	6.3	Enter White River National Forest Cliff north of road formed by Tie Gulch Member.

From last stop	Total	
.4	6.7	Brown cliff 30 m above road on right is Tie Gulch Member of Lower Ordovician Manitou Formation. Underlying beds are Dean Horse Member of Manitou containing thin beds of flat-pebble or edgewise conglomerate. In this area Tie Gulch Member is about 20 m thick and Dead Horse Member is about 30 m thick. Slopes below cliff are best collecting locality.
.1	6.8	Road cut in Dotsero Formation. Clinetop algal limestone member is thick, wavy bed at base of cliff, about 25 m above highway.
.3	7.1	Cross French Creek. North of bridge cliff of Manitou Dolomite and upper part of Dotsero Formation. Clinetop algal limestone (upper unit of Dotsero Formation) is 1.2 m prominent bed, 50 m above valley floor. Dotsero Formation here is about 30 m thick.
.1	7.2	Cliff of upper part of Sawatch Quartzite.
.6	8.0	Contact between Precambrian and Sawatch Quartzite 3 to 4 m above highway.
.3	8.3	Precambrian rocks on both sides of river. Inner canyon walls formed by Sawatch, Dotsero and Manitou Formations in a near-vertical cliff about 300 m high. Note that the upper 60 m of Sawatch Quartzite at base of sedimentary section consists of light-colored, dense, thin quartzite beds that give it a banded appearance. Notch in cliff below banded beds is formed by a glauconitic sandy dolomite 23 m thick. Total thickness of Sawatch Quartzite is about 150 m.
.5	8.8	On left is contact of Sawatch with Precambrian.
.3	9.1	Hanging Lake Trail and Deadhorse Creek. Precambrian exposed on either side of river.

STOP 1. Paleozoic stratigraphy in Glenwood Canyon (Figure 1).

The Sawatch Formation, Dresbachian through Trempealeauan in age, is the oldest Paleozoic formation in Glenwood Canyon. The Sawatch is composed of about 150 m of quartz sandstone except for 15 to 25 m of sandy dolomite to dolomitic sandstone 15 to 45 m below the top of the formation. From a distance the Sawatch can be recognized by the light to dark brown color banding in the lower cliffs of the canyon.

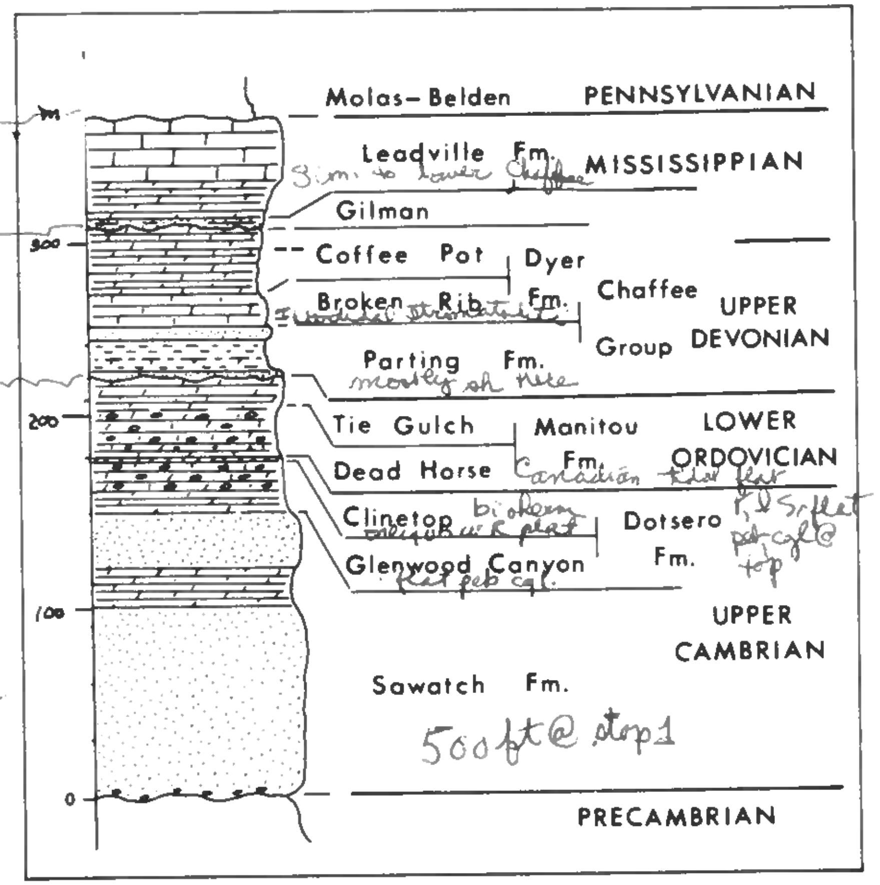


Fig.1 —Generalized stratigraphic section, Glenwood Canyon.

Conformably overlying the Sawatch is the Trempealeauan Dotsero Formation. The Dotsero consists of thin-bedded dolomite, dolomite or limestone flat-pebble conglomerate, and an upper persistent lavender to white algal carbonate bed about 1.5 m thick. The lower carbonate beds are called the Glenwood Canyon Member and the algal bed the Clinetop Member. The Dotsero generally forms a small grass or tree covered bench about two thirds of the way up the cliff in the canyon. The Dotsero is 21 to 40 m thick.

The Lower Ordovician, Canadian, Manitou Formation conformably overlies the Dotsero Formation. The Manitou has been divided into two members. The lower sequence consists of thin-bedded dolomites or limestones that contain flat-pebble conglomerate and is called the Dead Horse Member. The upper sequence consists of thin-bedded dolomite with few flat-pebble conglomerates and is called the Tie Gulch Member. The thickness of the Manitou ranges from 25 to 55 m, and it forms the brown upper one-third of the cliff in Glenwood Canyon.

The unconformity between the Manitou and the overlying Chaffee Group is the major unconformity in the Lower Paleozoic rocks in the canyon as well as in all of Colorado. All of the Middle and Upper Ordovician, all of the Silurian, and the Lower and Middle Devonian are absent in the Canyon. This unconformity is present at the top of the cliff.

The large tree and grass covered bench at the top of the prominent cliff in the canyon marks the position of the Upper Devonian Chaffee Group. The lower part of this slope consists of shales, quartz sandstones, and a few dolomite beds of the Parting Formation. The Parting ranges from 20 to 30 m thick and from Frasnian to Famennian in age. The upper part of the bench consists of the carbonate beds of the Dyer Formation. The lower part of this carbonate sequence is the very fossiliferous, gray, massive limestone which has been designated the Broken Rib Member, whereas the upper thin-bedded dolomite has been designated the Coffee Pot Member. The Dyer ranges from 50 to 55 m thick and in age from Famennian to Lower Mississippian, Kinderhookian. The top unit of the Chaffee Group is about 1.5 m of irregularly bedded sandy dolomite or dolomitic sandstone that is called Gilman Sandstone.

Conformably overlying the Dyer Formation are the light colored carbonates of the Leadville Formation. The lower one-third to one-half of the Leadville consists of thin-bedded dolomite beds of the Redcliff Member, which are very similar to those of the Coffee Pot Member of the Dyer. The upper part of the Leadville consists of fossiliferous and commonly cliff-forming and oolitic limestone of the Castle Butte Member. The age of the Leadville ranges from Kinderhookian to Osageian and the thickness from about 15 to 60 m.

The irregularity in thickness of the Leadville is largely due to post-Leadville, Late Mississippian, erosion, which produced karst topography and a soil zone on top of the Leadville called the Molas Formation. This soil zone is on top of the Devonian at some localities. The red and yellow streaks on the Leadville cliff are due to wash from the Molas. The Pennsylvanian Belden Formation unconformably overlies the Molas in the canyon.

From last stop	Total	
.7	9.8	Shoshone dam and intake.

From last stop	Total	
.2	10.0	Big rapids on left (when river is running). Several fatalities among rafters have occurred here. Now off limits for boating.
1.0	11.0	Pegmatites in road cuts.
.5	11.5	Note potholes in polished gray granite in river bed.
.7	12.2	Shoshone power plant. Penstocks bring water down from tunnel carrying water from Shoshone Dam 4 km upstream.
1.4	13.6	Green epidote and pegmatites in exposures on right.
.4	14.0	Cross Grizzly Creek. Heart of river-rafting stretch of Colorado River. Precambrian rocks exposed here consist of granites, pegmatites and gneisses.
.9	14.9	Leave White River National Forest. Thin-bedded Sawatch Quartzite across river.
.6	15.5	Sawatch Quartzite exposed on both sides of canyon.
.2	15.7	Across river, gray ledge of Leadville Limestone. High brush-covered slopes are formed on Belden Formation and lower part of Minturn Formation.
.6	16.3	Cross fault. Manitou on east against Leadville on west.
.3	16.6	No Name Exit. No Name Creek.
.3	16.9	Molas Formation, red residual soil on right covering karst surface of Leadville Limestone Cliffs on south side of river contain all formations from Sawatch Quartzite to Leadville Limestone.
.4	17.3	Leadville Limestone in road cut. Precambrian on left. Normal fault ahead and 1:00 at mouth of tunnel, which is in Proterozoic metasedimentary rocks.
.2	17.5	Exit tunnel.
.1	17.6	Cambrian-Precambrian contact.
.2	17.8	Railroad tunnel across river in Sawatch Quartzite (Cambrian).
.1	17.9	Enter Glenwood Springs.

From last stop	Total	
		The town of Glenwood Springs, elevation 1751 m (5745 ft) at the confluence of the Colorado and Roaring Fork rivers, was founded in 1882 by the Defiance Town and Land Co. It became the seat of Garfield County, organized the following year. The host springs and mineral springs and the scenic beauty of the valley had long attracted the Ute Indians to this area because of the "miraculous healing powers" of the hot waters for both man and animals. It was not until 1882 that White man dreamed of turning the springs into a health spa. The Glenwood Hot Springs pool was constructed in 1888 after the Colorado River had been diverted from its original course north of the present Main Lodge to its present course. The original bathhouse was completed in 1891. The main spring has a daily flow of 16,350,000 liters of water at a tempearture varying from 51 to 54°C (124-130°F). One of the most notorious of Glenwood Springs inhabitants was John Henry "Doc" Holliday, who came for the cure and is now buried here, having died of turberculosis in 1887.
.1	18.0	Across river, Dotsero Formation (Cambrian) and Manitou Formation (Ordovician) are exposed as thin-bedded units. Leadville Limestone at top of cliffs. Several normal faults with small displacements, down on northeast side, visible in cliff
.1	18.1	Chaffee Group (Devonian) exposed across river.
.1	18.2	Across river, Leadville Limestone forms massive cliff exhibiting solution cavities.
.1	18.3	Road-cut in Leadville Limestone. Hot springs in river bed south of highway. Strong order of H_2S.
.1	18.4	Excellent exposure of Molas Formation (Pennsylvanian red beds) resting on and filling sinks in karst in Leadville Limestone on right. A good section of Belden Formation, 185 m thick, is present across the river above the houses.
.2	18.6	Vapor Springs Lodge and vapor caves in Leadville Limestone.
.5	19.1	Leadville Limestone outcrops on right. Exit 116. Glenwood Springs-Carbondale-Basalt-Aspen.
.8	19.9	Good exposures of Belden Formation on right of highway.

From last stop	Total	
.5	20.4	Rest Area. Broad fan at foot of red hill on south side of Colorado River. Red beds in the upper slope of the hill in the Maroon Formation (Pennsylvanian-Permian). Yellowish exposures in the long slope in the Eagle Valley Formation.
.8	21.2	Exit 114. West Glenwood Springs. At 3:00 Leadville Limestone and Belden Formation (Pennsylvanian) dipping toward observer. Note travertine terraces and spectacular exposures of outwash gravels on right.
.4	21.6	Light-tan and gray Eagle Valley (Minturn Formation) evaporites of Pennsylvanian age exposed at 3:00.
1.7	23.3	Good exposure of tongue of the Weber Sandstone at top of slope at 7:00. Maroon Formation about 1050 m thick here and dips steeply to southwest off White River Uplift, visible to northeast.
.8	24.1	Exit 111 South Canyon Creek. Take exit, cross under I-70 and bear left.
.4	24.5	Cross Colorado River. Maroon Formation exposed in cliffs.
.2	24.7	White sandstone on left is tongue of Weber Sandstone, the major producing zone in the Rangely oil field.
.1	24.8	State Bridge and Chinle Formations on left. State Bridge Formation is about 30 m thick and contains a bed of gray marine limestone 2 m thick, the South Canyon Creek Member, of Permian age (Bass and Northrop, 1950). The State Bridge here is composed of shale and siltstone. The Chinle about 70 m thick has a distinct orangish hue compared to the State Bridge and is composed of shale, siltstone, and limestone pebble conglomerate.
.1	24.9	Entrada Sandstone and Morrison Formation on left. The Entrada is a light gray sandstone, locally cross bedded, and is about 30 m thick. The Morrison, about 170 m thick consists of interbedded pale green, grayish red shale, light gray sandstone and a few beds of dark gray limestone.
.1	25.0	Dakota Sandstone on left. Sandstone with interbeds of sandy shale and shale. Chert and sandstone pebble conglomerate near the base. About 50 m thick.
.1	25.1	Mancos Shale.

From last stop	Total	
.1	25.2	STOP 2. We will examine the section from the lower part of the Mancos down to the tongue of Weber Sandstone (Fig. 2). Buses will pick us up by the bridge over the Colorado River.

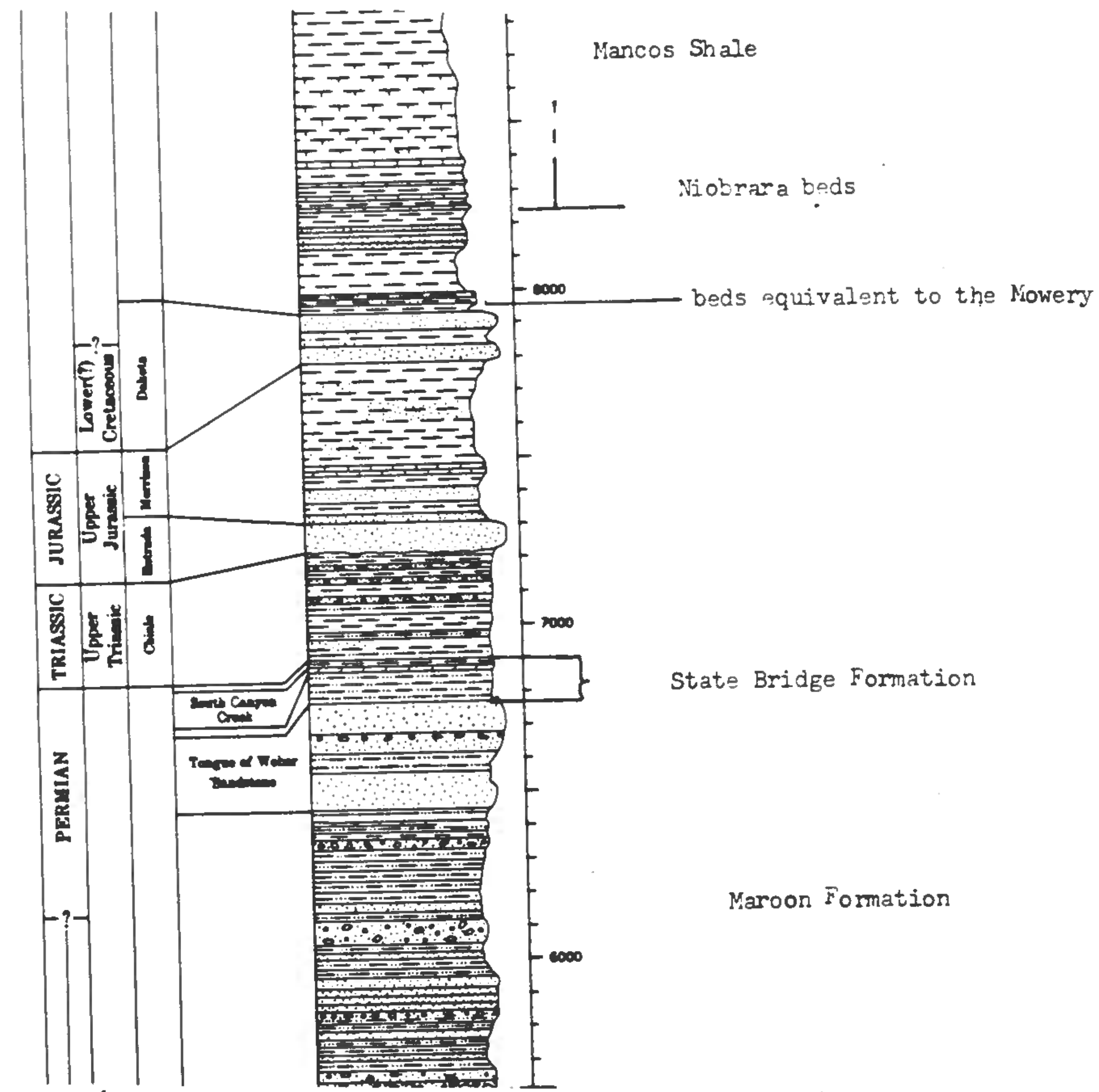
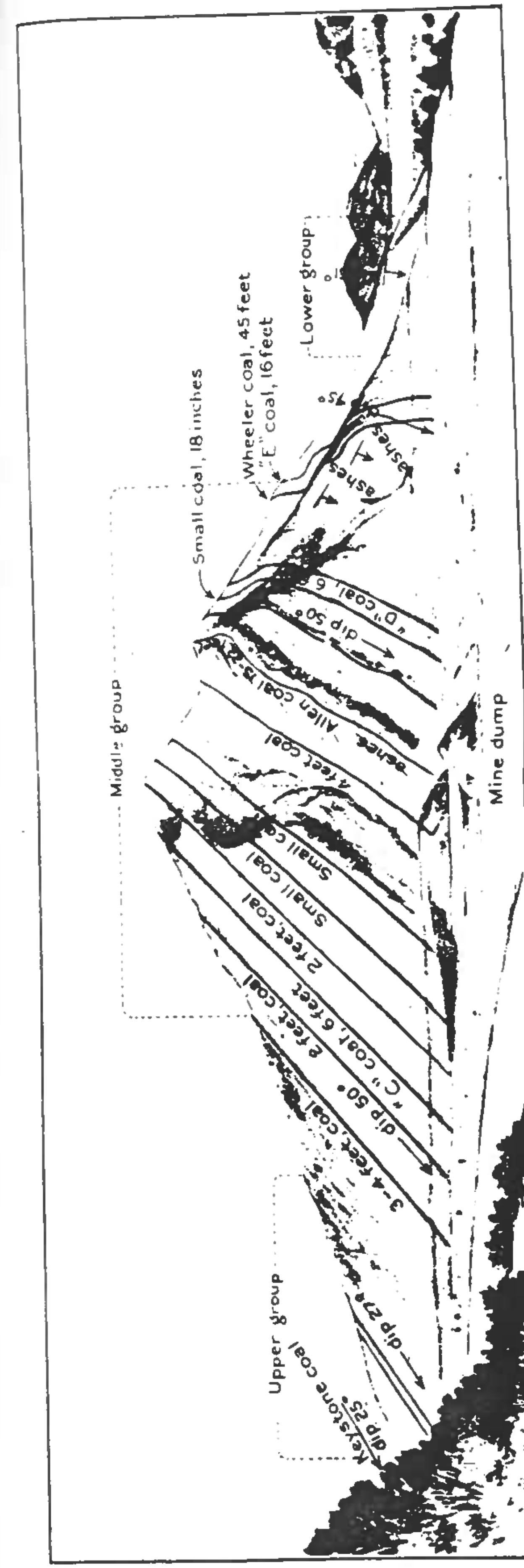


Fig.2 Stratigraphic section at STOP 2 Bass and Northrop, 1963

Road Log resumes at Exit 111.

From last stop	Total	
1.0	26.2	Mud cracks and ripple marks exposed on parting surfaces of steeply dipping Maroon sediments on north (right) side of road.
.6	26.8	Maroon Formation exposed on both sides of canyon. Light-colored Weber Sandstone caps slope on ridge to left (south).
.5	27.3	Exit 109. Canyon Creek.
.5	27.8	On left, exposures of the section we visited on South Canyon Creek.
.7	28.5	Chacra railroad signal house on right. Chain link fence across river at 9:00 (south) is dinosaur quarry in Morrison. Museum of Western Colorado (Grand Junction) removed some disarticulated bones of mixed dinosaur species. Nearby to the east at river level is an old prospect pit for uranium in the Morrison.
.4	28.9	Dakota Sandstone forms hogback on left. Morrison Formation exposed below on north slope. Chinle Formation exposed on right of highway.
.3	29.2	Outcrops at 3:00 (north) of Siliceous shale at the base of the Mancos equivalent to the Mowry Shale. Overlain by river gravels.
1.5	30.7	In broad valley eroded in Mancos Shale.
.2	30.9	At 9:00 (south) is tipple formerly used to load coal mined from Wheeler and Allen coals in the Mesaverde Group. Small depressions along foot of slope mark position of mined and burned Wheeler coal.
.5	31.4	Exit 105 to Newcastle. Take exit, turn right and then left on U.S. Highway 6, pull off on right and STOP 3, at a monument to those killed in the local coal mines. Coal Ridge to the south; at east end is section from upper Mancos Shale to resistant sandstones of the Mesaverde Group; Corcoran and Cozzette sandstones are two resistant beds amid the uppermost Mancos Shale. Coal is present in three main zones each above a unit of regressive sandstone unit, the lowest is the Rollins, or Trout Creek sandstone. Reddish colors mark burned coal in each zone. The continuation of the ridge north of the Colorado River is Burning Mountain. Looking down valley Mesaverde exposures show flattening of dip from Grand Hogback into the Piceance Creek Basin (Fig. 3). Lower exposures dip 45 to 55°; uppermost



II. DIAGRAM SHOWING POSITION OF COAL BEDS IN THE NEWCASTLE SECTION.
Identification of coals based on information furnished by Mr. Perry Coryell, of Newcastle.

Gale, 1910

Fig. 3

From last stop	Total	
		visible beds are at level of the Keystone coal (about 600 m above the base of the Mesaverde), and dip is about 25°.
		Return to I-70 heading west.
2.6	34.0	New subdivision of town across river. Red slopes on right formed of clinkers produced by burning of Wheeler and Allen coal beds at base of main part of Mesaverde. Contact with upper Mancos Shale tongue concealed here.
		Entering the Piceance Creek basin. Beds of Paleocene and Eocene age dip at progressively lower angles up-section into the basin.
.5	34.5	On right at 3:00, yellowish-white sandstone below purple -red Wasatch sandstone is Ohio Creek Fm. In other parts of the Piceance Creek Basin Johnson and May (1980) have interpreted the Ohio Creek Formation as the uppermost member of the Mesaverde representing a zone of intense weathering during early and middle Paleocene time.
3.5	38.0	Road cut on right shows Wasatch capped by outwash gravels.
1.3	39.3	Exit 97 to Silt and to Divide Creek gas field that produces from the Mesaverde Formation in the high area on the skyline to the left.
.9	40.2	Cross Colorado River. Note loess bluff on right.
.6	40.8	"Pediment" or bajada remnants at 3:00 still attached to hills.
5.0	45.8	At 3:00, across river is site of old Carbide uranium-vanadium mill and grassed over tailings pile. Note outwash gravels and loess in hill behind millsite.
.6	46.4	Exit 90. Rifle-Meeker. Colorado highways 13 and 789 give access to Piceance Creek basin oil shale developemnt and to coal mining operations near Meeker and Craig. In August 1972, artist Cristo erected orange nylon curtain 900 m long across Rifle Gap, a watergap in the Grand Hogback about 10 km northeast of town.
.6	47.0	Bluff above floodplain on left probably mostly Pleistocene loess derived from floodplain.

From last stop	Total	
1.0	48.0	Cross Colorado River.
1.4	49.4	Cross railroad.
.6	50.0	Exit 87. West Rifle.
1.7	51.7	Major drainage at 9:00 across Colorado River is Porcupine Creek. Nearly 450 m of Wasatch, Green River and Uinta Formations are exposed in cirque-like features in upper reaches of the creek. Above Porcupine Creek, the highest know on Battlement Mesa is North Mamm Peak, elevation 3390 m (11,123 ft.) a remnant of a basalt flow about 10 m.y. old.
.4	52.1	Crest of Webster Hill.
.1	52.2	Good exposures of Shire Member of Wasatch on rights. Prominent River terraces at 9:00.
2.0	54.2	Turn right onto exit. Turn right twoard Paraho Oil Shale Demonstration Plant and Naval Oil Shale Reserves 1 and 3.
.3	54.5	View ahead of local section. Road ascends on sage-covered alluvium of Sharrard Park. Variegated beds of the Shire Member of the Wasatch Formation are exposed in juniper-pinon-covered hills at 9:00 and 1:00 and continue up slope to highest pinkish or reddish beds. Overlying the Wasatch and inter-fingering with it are siltstone, sandstone and marlstone beds of the Anvil Points Member (equivalent to Douglas Creek and Garden Gulch Members and lower part of Parachute Creek Member) of the Green River Formation. These beds weather to brown and tan and are overlain by whitish-weathering precipitous slopes of the Parachute Creek Member. This member contains the richest oil shale beds of the Piceance Creek basin. In this area the Mahogany ledge occures as the first dark bluish-gray- weathering, resistant ledge exposed above the vegetated talus slopes below the steep cliffs (note road leading to portals at 11:00). A 21-m-thick section of shale in the Mahogany ledge averages about 93 l of oil/tonne (27 gal/ton), and of that section 19 m average 103 l (30 gal). Above the Mahogany ledge, about 140 m of oil shale average 34 to 52 l/tonne (10-15 gal/ton). The upper rounded portion of the cliffs is made by sandstone of the Uinta Formation. Uinta supprts cover of aspen, spruce and Douglas fir.

From last stop	Total	
1.0	55.5	Turn right at sign pointing to Research Center.
.4	55.9	Contact at 2:00 between Wasatch (below) and Green River (above) follows top of continuous red beds.
.3	56.2	Turn left into parking lot. STOP 4. Guard station and gate to Paraho Research Center to the right.

Use of sh a misnomer; actually a marl-stone

The Anvil Points mine and the Research Center, located about 1.5 miles to the southeast of the mine, are on Naval Oil-shale Reserves Nos. 1 and 3. These reserves were withdrawn from location in 1916 and 1924 to assure the U.S. Navy of a secure source of fuel. The research center is at an altitude of about 5700 feet. This is approximately 200 m below the Green River-Wasatch contact. The mine portal is at a distance of 5.5 miles by road, is at an altitude of 8200 feet in the Mahogany Ledge. The lower part of the Parachute Creek Member, below the Mahogany Ledge, is about 90 m thick. It forms steep, white-weathering slopes that contain thin, ledgy oil shale beds. The Green River Formation below the Parachute Creek Member consists mainly of marginal lacustrine sediments; siltstone, sandstone, algal limestone, and oolitic and ostracodal limestone and sandstone of the Anvil Points Member. This member contains in the upper half interbeds of marlstone and low grade oil shale like the Parachute Creek Member. Battlement Mesa, south of the Colorado River, is completely underlain by the Green River and Uinta Formations and capped by a series of basalt flows. The Mahogany Ledge and overlying oil shale beds of the Green River Formation form the white cliffs and steep slopes exposed along the north face of the mesa. The lower slopes of the mesa consist of semi-consolidated or unconsolidated deposits of Quaternary and possibly late Pliocene age. These deposits delineate eight former levels of the Colorado River that indicate a former stream gradient of 11 feet per mile similar to that at present (Yeend, 1969).

The Anvil Points facility has been operated intermittently since 1945. The first 10 years of mining, crushing retorting, and refining research was conducted by the U.S. Bureau of Mines. In recent years research has been by private industry under a federal lease of the facility. A total of more than half a million tons of oil shale have been mined and approximately 150,000 barrels of shale oil produced in a pilot shale operation since 1945.

Return to Glenwood Springs for bed and board.

Saturday, October 2. From Glenwood Springs we follow the Roaring Fork to Aspen. The Eagle Valley Formation, in part brought up by the Cattle Creek diapiric fold, forms much of the valley side southeast to near Basalt. From there the valley is along the Castle Creek fault zone, slices through the eastern end of the Roaring Fork syncline, crosses the Castle Creek fault zone, and reaches the west margin of the Sawatch Range at Aspen

From last stop	Total	
.0	.0	Road log starts at the Colorado River on Colorado Highway 82.
.7	.7	On right, Eagle Valley Formation having predominantly gray and yellowish gray siltstone, sandstone, and gypsum overlain by red sandstone, siltstone, shale, and conglomerate of the Maroon Formation.
.6	1.3	Bear leaft at Y intersection. View of Mt. Sopris (3,947 m) ahead.
1.3	2.6	Remanant of high level gravel at 1:00. Lower terrace with airport on it is the Pindale outwash terrace.
.7	3.3	Beehive ovens for making coke across valley at 2:00.
.2	3.5	Large exposures of Maroon Formation on left.
1.4	4.9	Pre-Bull Lake outwash terrace at 1:00 may have been tilted away from the valley axis by Quaternary movement on the Cattle Creek Diapir.
.9	5.8	Exposure of Eagle Valley Formation at 2:00.
.7	6.5	Colorado Mountain College road to left.
.4	6.9	Eagle Valley Formation overlain by Maroon Formation across valley at 3:00.
.8	7.7	Cottonwood Pass road and Cattle Creek. Across the river to the west Shannon Oil Co. No. 1 Rose encountered 633 m of interbedded evaporite and micaceous siltstone above 285 m of halite with minor interbeds of anhydrite and siltstone to the bottom of the well (Mallory, 1966).
.9	8.6	Bull Lake outwash terrace at 1:00. Four major terrace levels occur in the Carbondale area where they have recently been studied by L.A. Piety of the University of Colorado.

From last stop	Total	
1.8	10.4	Coal loading facility spans Roaring Fork River to right.
1.0	11.4	Scenic overlook. Turn off and STOP 5. View of Mt. Sopris, up the Crystal River valley and towards the Grand Hogback. The four main terraces are of Pinedale, Bull Lake, and pre-Bull Lake (2) age. The lower of the two pre-Bull Lake terraces contains a lens of Pearlette type O age, about 600,000 years old. These terraces cannot be traced to the terminal moraines near Aspen because of the steep sides of the intervening Snowmass Canyon. Terminal moraines are not well developed in the Crystal River drainage. If the light is right, one can see rock glaciers on the north and northwest sides of Mt. Sopris. Birkeland (1973) concluded that some of the glaciers are as old as Bull Lake age and that some rock glaciers that initially formed in late Pinedale are presently active. Mt. Sopris is the northwesternmost outlier of a number of intrusive bodies in the Elk Mountains. To the left of Mt. Sopris are rounded hills underlain by Mancos Shale in the west end of the Roaring Fork syncline. The shale is overlain by gravel which probably is of Late Tertiary age like the basalts in the region. To the northwest is basalt forming a surface that appears to slope gently north. The basalt has been broken by numerous parallel faults with their west sides down, a pattern that Murray (1969) interpreted to be due to unfolding of the Grand Hogback monocline. These basalts were correlated with the 9 to 14 m.y. old group 2 basalts by Larson and others (1975), but they have not been dated. Since they have a structural relief of 850 m, a date on them would be important in deciphering the Neogene structural history of the area. To the west, ridge-forming sandstones of the Dakota and Mesaverde form the southern extension of the Grand Hogback.
.8	12.2	Junction of Colorado Highway 133 to Carbondale and Redstone.
.4	12.6	Large roadcut on left in sandstone and siltstone of the Maroon Formation.

From last stop	Total	
2.1	14.7	On left, exposure of Pleistocene terrace gravel correlated with the Pinedale by Piety (1981).
1.1	15.8	Crossroads at Catherine; to the left is a large plateau capped by 8.7 m.y. old alkali olivine basalt (Larson and others, 1975) associated with river gravels and overlying the Eagle Valley Formation. Basalts covered the floor of a broad valley eroded in the Eagle Valley, and the valley has been deepended only 150 m since their extrusion.
.6	16.4	Eagle Valley Formation exposed on both sides of valley.
1.0	17.4	At 11:00 is Basalt Mountain (3,311 m), a shield volcano formed by 20 or more flows of alkali olivine basalt about 9 m.y. old (Larson and others, 1975). The lavas rest on incompetent Mancos Shale. A landslide with an area of about 26 km^2 extends from the edge of the basalt cliffs near the top of the mountain nearly to the valley bottom.
1.7	19.1	Intersection with El Jebel road.
1.8	20.9	Across valley at 3:00 exposures of the upper part of the Maroon Formation, Entrada Sandstone, Morrison Formation, and Dakota Sandstone (the big ledge). State Bridge and Chinle Formations are missing. Thinning of the State Bridge by erosion prior to deposition of the Chinle and thinning of the Chinle by erosion prior to deposition of the Entrada can be demonstrated in this area.
.8	21.7	We have crossed a fault bounding a graben that extends southeast along the Castle Creek fault zone and to the north under Basalt Mountain. Eagle Valley Formation on the west is faulted against Mancos Shale on the east. Rocks of Jurassic and Cretaceous age occur beneath the valley to the southeast, and rocks of late Paleozoic and Triassic age crop out on the hills on either side. Interpretation of a simple graben is based on very poor exposures in the valley.
.6	22.3	On left Mancos Shales crops out in the graben.
.6	22.9	Intersection with Fryingpan River road at Basalt. Colorado Midland Railroad line to Aspen crossed the Sawatch Range and came down the Fryingpan whence it headed up the Roaring Fork.

From last stop	Total	
.1	23.0	Cross Fryingpan River. Low hill at valley bottom to left formed by Morrison Formation dipping towards us is at east margin of graben.
1.1	24.1	To the right along the valley side the light colored rocks are Entrada Sandstone and Dakota Sandstone, which are in fault contact with Maroon Formation to the south. The southernmost exposures of the Permian South Canyon Creek Member of the State Bridge Formation are in the low hills to the left.
.6	24.7	Railroad crossing.
.3	25.0	Southeast end of graben.
.1	25.1	Cross Roaring Fork River.
.4	25.5	Across the river the contact between the Maroon Formation and the overlying State Bridge Formation is about 100 m above the river.
.9	26.4	Cross Snowmass Creek. The Castle Creek fault probably extends along the valley here but produces little stratigraphic separation. The valley bottom is along the crest of an anticline. At 11:00 hills formed by Maroon and State Bridge Formations.
.1	26.5	Snowmass Creek road to right.
1.0	27.5	Roadcut in Maroon Formation.
.9	28.4	Across the river in the lower outcrops, the beds of the Maroon Formation can be seen dipping eastward more steeply than the beds of the State Bridge Formation in the higher outcrops. The angular unconformity is about 30° here. Ahead white outcrops are Eagle Valley in slices along Castle Creek Fault zone.
.7	29.1	Roadcut exposure of thin, even-bedded sandstone, siltstone, and claystone of the State Bridge. Characteristic parallel ripple marks and rounded coarse sand grains can be seen here.
.1	29.2	The low-level exposures across the river are in Maroon Formation.
.1	29.3	Cliffs along the skyline, across the river, are the State Bridge Formation.

From last stop	Total	
.2	29.5	To the right, the bold outcrops are State Bridge Formation, with its coarse unit of Toner Creek at the top and the Sloane Peak Member in the lower part of the cliff; both members are of Triassic age.
.4	29.9	To the left the dark red unit is composed of sandstone and siltstone of the Chinle Formation overlain by light tan sandstone of the Entrada.
.4	30.3	Intersection with road across Watson Divide, which separates the Snowmass Creek valley from the Roaring Fork valley and has a remnant of a gravel deposit containing boulders of basalt from the hill on the left. The deposit is correlated with terrace D of middle Pleistocene (?) age and show that at that time the Roaring Fork did not flow through the narrow canyon from which we have just emerged. To the left across the river the greenish gray sedimentary rocks are Morrison Formation.
.3	30.6	Road to Woody Creek goes left. The lowest outcrops across the river are the Burro Canyon Formation and the Dakota Sandstone. Top of hill to left capped by flows of alkali basalt about 1.5 m.y. old (Larson and other, 1975).
.7	31.3	On the left below road level, are two terraces. The lower is of local extent. The one just below the road is alluvial terrace A that is probably Holocene inasmuch as its width is that of the present meander belt of the Roaring Fork and it occupies a low topographic topographic position. Piety (1981 interprete this terrace as being of Pinedale age, and we showed it as Quaternary on our published geologic map. Above the road to the right is terrace B, the youngest extensively developed Pleistocene outwash terrace.
.8	32.1	On the left, the pile of brown rock is iron ore waiting to be shipped. The ore is trucked here from a mine located at the head of the Castle Creek valley south of Aspen. This loading facility is now at the end of the Denver and Rio Grande Railroad branch that served Aspen from 1887 until 1969.

STOP 6. Looking northwestward back down the Roaring Fork the prominent hill to the west of the canyon is underlain by bedrock that dips southward 25 to 30° towards the Roaring Fork syncline. Resistant Dakota Sandstone is underlain by Burro

From last stop | Total

Canyon, Morrison, Curtis, Entrada, Chinle, and State Bridge Formations. These formations continue unbroken northeast across the canyon to the Castle Creek fault zone that passes through the crest of the hill northeast of the Roaring Fork. That hill is capped by the remains of a cinder cone resting on about 120 m of basalt flows about 1.5 m.y. old. The base of the basalt which flowed out on the floor and side of the Roaring Fork valley about 1.5 m.y. ago is about 375 m above the modern Roaring Fork. In the hills of Mancos Shale to the west large blocks of basalt are present as much as 200 m above the present valley bottom and may represent lag from flows covering a broad valley eroded in Mancos Shale. Watson Divide west of the basalt-capped hill is floored by gravel with basalt cobbles and is about 150 m above the Roaring Fork. Possibly prior to and immediately following the eruption, the Roaring Fork turned westward about at this stop and followed the Roaring Fork syncline in the area of present Besancon Gulch to Snowmass Creek. Watson Divide could have been a later site of the Roaring Fork before it was captured and cut its present canyon through the Maroon and State Bridge Formation.

The canyon east of the basalt-capped hill (Red Canyon) exposes State Bridge Formation dipping about 20° eastward in the upper slopes. Maroon Formation beneath dips much more steeply and is vertical adjacent to the basalt flow and the Castle Creek fault zone. Within the fault zone white gypsiferous beds of the Eagle Valley Formation crop out in the lower slopes on both sides of the mouth of Red Canyon.

To the southeast are three major outwash terraces that we will follow upvalley to their associated moraine deposits (Fig. 4). Two miles upvalley where the uppermost terrace is well preserved, the terraces, designated D, C, and B on the published geologic maps, are abot 195, 145, and 50 m above the Roaring Fork, respectively. Terrace B, on which we have been travelling, heads at end moraines east and south of Aspen, which are breached by narrow gorges. Terraces C and D head below lateral moraines several km downvalley from the B terminal moraines. No ages of the moraines and terraces are available, but it seems reasonable to correlate the B terraces and moraines

From last stop | Total

with the Pinedale, the C terrace and moraine with Bull Lake and the D terrace and moraine with pre-Bull lake. Below us along the river is terrace A only 15 m above stream level.

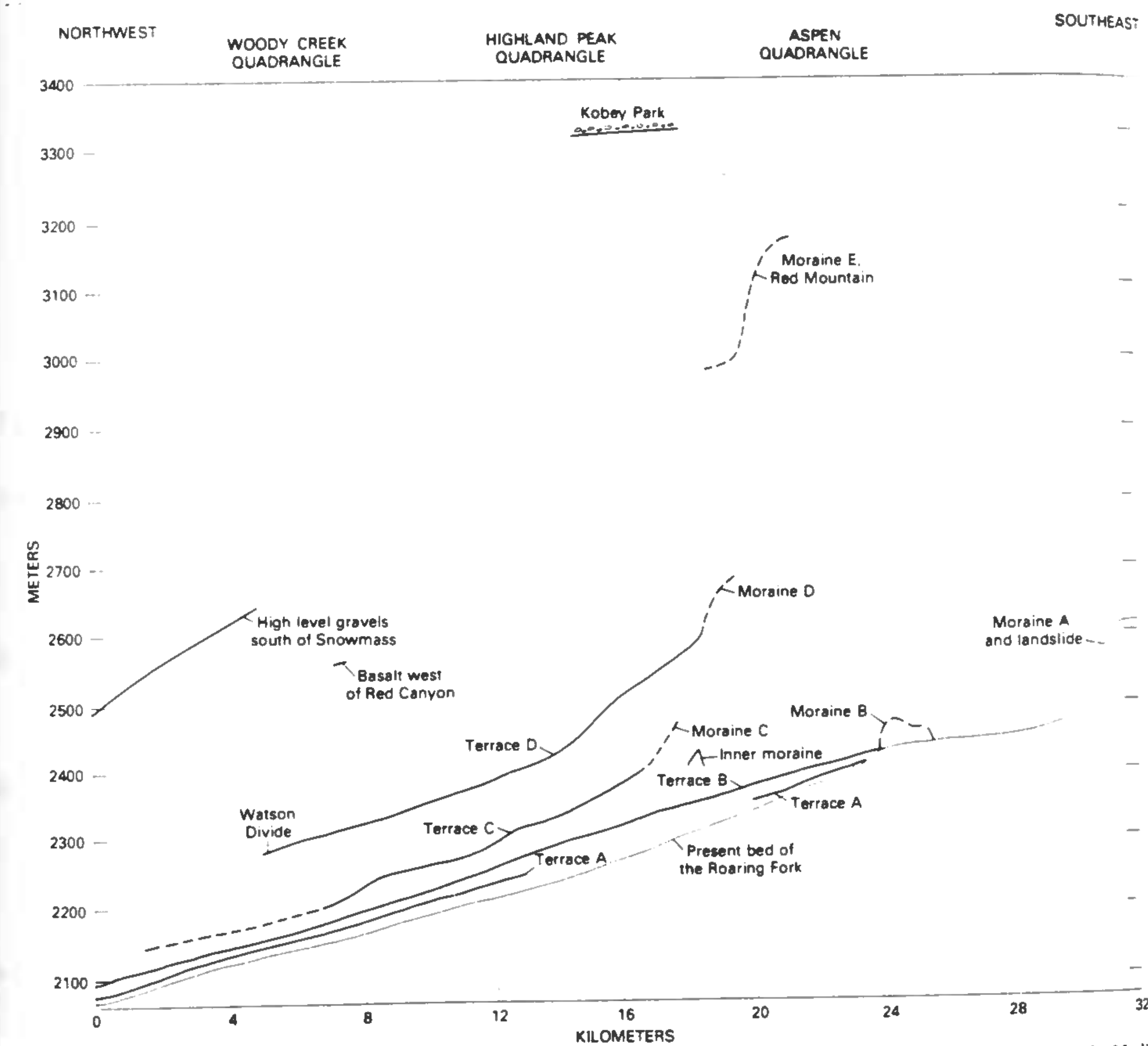


Fig.4 Profile along the Roaring Fork River valley showing present stream grade, terrace levels, moraines, and older gravels. Modified from Bryant (1971a, 1972a) and Freeman (1972a, b). Dashed line indicates surface of moraine.

Bryant, 1979

From last stop	Total	
.7	32.8	At 3:00 Eagle Valley Formation along the Castle Creek fault zone forms white outcrops.
.8	33.6	On right, ledge forming sandstone marker bed in the Mancos Shale reaches the valley bottom in the trough of the Roaring Fork syncline. This sandstone immediately underlies the Didymoceras stevensoni Zone about 72 m.y. old (Obradovich and Cobban, 1975). A hill to the west (out of sight when travelling this direction is capped by a sandstone above the Baculites compressus Zone, which is believed to mark the base of the Mesaverde Formation and is the youngest bed known to be preserved in the Roaring Fork syncline.
.2	33.8	Road left to Woody Creek and Lenado. We are travelling on terrace B (Pinedale). Terraces C and D at 10:00 are Bull Lake and pre-Bull Lake in age.
.7	34.5	Brush Creek road to the right leads to Snowmass ski area and resort. Our route to Aspen follows much of the grade of the Colorado Midland Railroad, which was in service from 1888 to 1918.
.2	34.7	Cuts in Mancos Shale in the Baculites gregoryensis and Baculites scotti Zones for next four miles.
.4	35.1	Distant view of the Sawatch Range up the Roaring Fork valley.
.3	35.4	Outwash terrace B. This is the youngest extensive Pleistocene outwash terrace in the Roaring Fork valley. The river has cut only a narrow gorge in it here, and the terrace is graded to equally undissected terminal moraines located just east of Aspen and near the junction of the Castle Creek and Maroon Creek roads with Highway 82. Straight ahead is Aspen Mountain. Buttermilk Ski Area is at 1:00 and Highlands Ski Area is in the background.
.5	35.9	Cross Owl Creek. Straight ahead, low hill is subdued remnant of a recessional moraine correlated with moraine C although it is 1.5 km up valley from the farthest advance of glacier of C episode (Fig. 5). Red Butte at 11:00; the top is held up by overturned Entrada Sandstone.
.4	36.3	Exposures of Mancos Shale at 9:00.

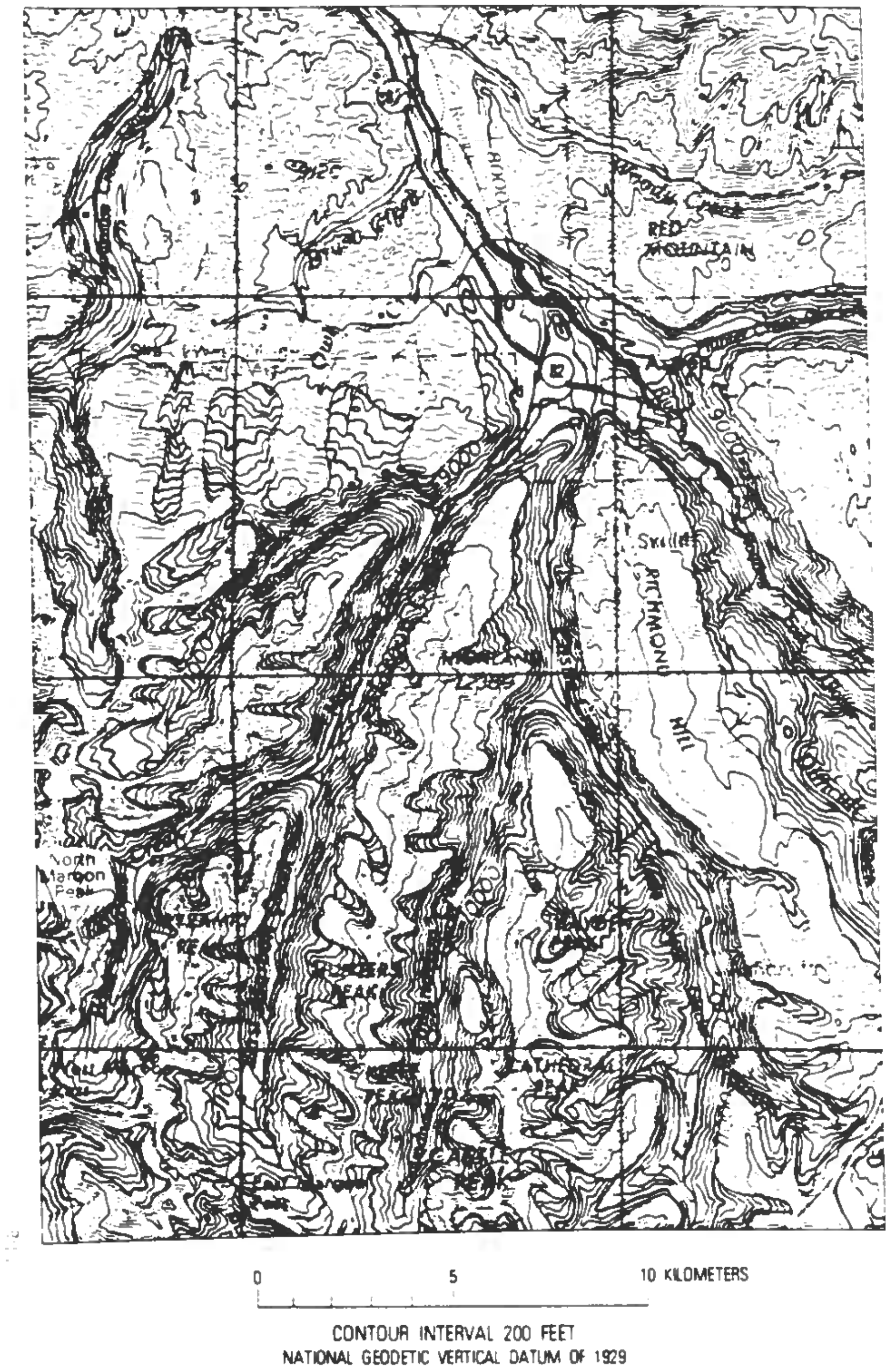


Fig. 5 —Glaciers in the Aspen area during maximum extent of Bull Lake(?) Glaciation. Drawn on basis of moraines and topography in Bryant (1969, 1970, 1971a, 1972a) and Freeman (1972a). Base from A.M.S. 1:250,000, Leadville, 1957.

Bryant, 1979

From last stop	Total	
.1	36.4	At 3:00 Snowmass Ski Area is on dip slope of south limb of the Roaring Fork syncline. The Dakota sandstone and Burro Canyon Formation underlie much of the upper part of the ski area. Mt. Daly is near the north edge of the Snowmass pluton, which is composed of Oligocene granodiorite. The stripe on Mt. Daly is altered zone in the granodiorite.
.4.	36.8	Aspen airport. Bulky lateral moraine of glacial episode C at 3:00.
.5	37.3	On left, hill formed by recessional moraine C.
.4	37.7	On right is Buttermilk Ski Area on dip slope in Mancos Shale. At 9:00 is Red Butte, composed of a slice of rock overturned along the Castle Creek fault zone. Prominent band of red soil is formed on the Chinle Formation. Above it on the slope is the State Bridge Formation, and the highest point on the ridge is capped by sandstone of the Sloane Peak Member of the State Bridge Formation. Downslope from the Chinle is Entrada Sandstone. Morrison Formation, Burro Canyon Formation, and Dakota Sandstone. Cross faults of small displacement cut the formations.
.3	38.0	Straight ahead, West Aspen Mountain composed of Manitou Dolomite, Peerless Formation (Cambrian) and Sawatch Quartzite overlying Precambrian quartz monzonite.
.2	38.2	Highlands Ski Area at 2:00. Mostley on dip slope of State Bridge Formation.
.2	38.4	Cross Maroon Creek.
.2	38.6	View of Pyramid Peak (4,273 m) up valley of Maroon Creek.
.4	39.0	Junction with roads that go up Castle and Maroon Creeks. Terminal moraine B to right is graded to terrace B on which we have been travelling.
.2	39.2	Hunter Creek valley ahead. To right of Hunter Creek is moraine-covered shoulder of Smuggler Mountain. Mine dump halfway up hill is from J.C. Johnson tunnel. The largest mines of the Aspen district were beneath Smuggler Mountain.
.2	39.4	Cross Castle Creek. At 2:00, dip slope of Manitou Dolomite on West Aspen Mountain.

From last stop	Total	
.5	39.9	Pride of Aspen mine dump at 3:00. Ore was in fractures adjacent to a fault bounding the uplifted block of West Aspen Mountain.
.3	40.2	View across park of Aspen Mountain Ski Area. Slopes are on faulted syncline between West Aspen and East Aspen Mountains. East Aspen Mountain, at 2:00, and Bell Mountain, just to the right of it, are composed of faulted, northwest-dipping lower Paleozoic rocks.
.1	40.3	Turn left at traffic light by Hotel Jerome.
.1	40.4	On terrace A of possible Holocene age.
.1	40.5	Cross Roaring Fork. Turn right.
.2	40.7	Turn left and STOP 7. Walk about .4 mile to dump below Smuggler #2 tunnel. The Smuggler is leased by Stephan Albouy from Smuggler-Durant, and he has kindly allowed us to come up here for an unobstructed view of the Aspen mining district.

View across the head of terrace B, the Pinedale outwash terrace, and the city of Aspen towards the Aspen Mountain syncline. The syncline is jammed between the margin of the Sawatch Range to the east and a horst along the Castle Creek fault zone and is faulted on both sides. The faults on the west side locally cut out all the Paleozoic section below the Belden Formation. On the east side the fault pattern is more complex, and many faults lie south of East Aspen Mountain and die out before they reach the valley bottom. The Aspen Mountain syncline is cored by dark gray limestone, dolomite, and shale of the Belden Formation, which contains near its base a sill of aplite porphyry (leucocratic granodiorite based on chemical analysis, Bryant, 1979, table 6). The syncline plunges north towards us at nearly the same angle as the valley side does.

The first mining claims were located on Spar Ridge in 1879, and a number of others, including the Smuggler, were staked during that season. The ore is found along two main stratigraphic horizons. One is at the contact between the dolomite and limestone members of the Leadville (Redcliff and Castle Butte Member, respectively of Nadeau, 1972). That horizon is exposed along the road into Spar

From last stop	Total

Gulch from the top of the chairlift in the lower left hand part of the ski area. The other horizon was at and near the contact between the Belden and the Leadville, which was the productive horizon on Smuggler Mountain, North of Aspen Mountain the limestone member of the Leadville is cut out by either pre-Belden erosion, faulting, or a combination of these two factors. Both longitudinal and cross faults occur in the district. The longitudinal faults dip steeply for the most part, and in many places it is difficult to determine with certainty whether breccia at the upper contact of the Leadville is sedimentary, tectonic, or a combination of the two. Transverse faults dip steeply on Aspen Mountain and dip moderately south on Smuggler Mountain. The best ore was found where cross faults intersect the favorable horizons.

The portal of the Smuggler #2 tunnel, in which work is now being done, is in mineralized dolomite of the Leadville just east of the contact with the Belden. The rock contains silver, lead, and zinc accompanied by cadmium (Bryant, 1977, table 9, samples 1458 a-c).

The Smuggler and the nearby Mollie Gibson were two of the largest mines in the Aspen district. The ore had a thick zone of secondary enrichment, and a nugget of native silver weighing 1840 lbs. after trimming to a size small enough to get up the shaft was taken from the Smuggler. Much of the ore produced after the demontization of silver in 1893 was milled just below us. Two railroads served Aspen from 1888 to 1918; the Denver and Rio Grande came up this side of the valley, and the Colorado Midland came up the south side and they connected in a big loop below us here.

Many of the larger mine dumps on Aspen Mountain have been modified by ski trail development. The dump at the valley bottom east of the ski area is at the lower Durant tunnel through which much of the ore mined during the later days of production was extracted after many properties had become consolidated. Continuous workings exist (flooded now) under the Roaring Fork valley, and the area mined extends 5 km along strike (Fig. 6) and over a vertical range of 1 km.

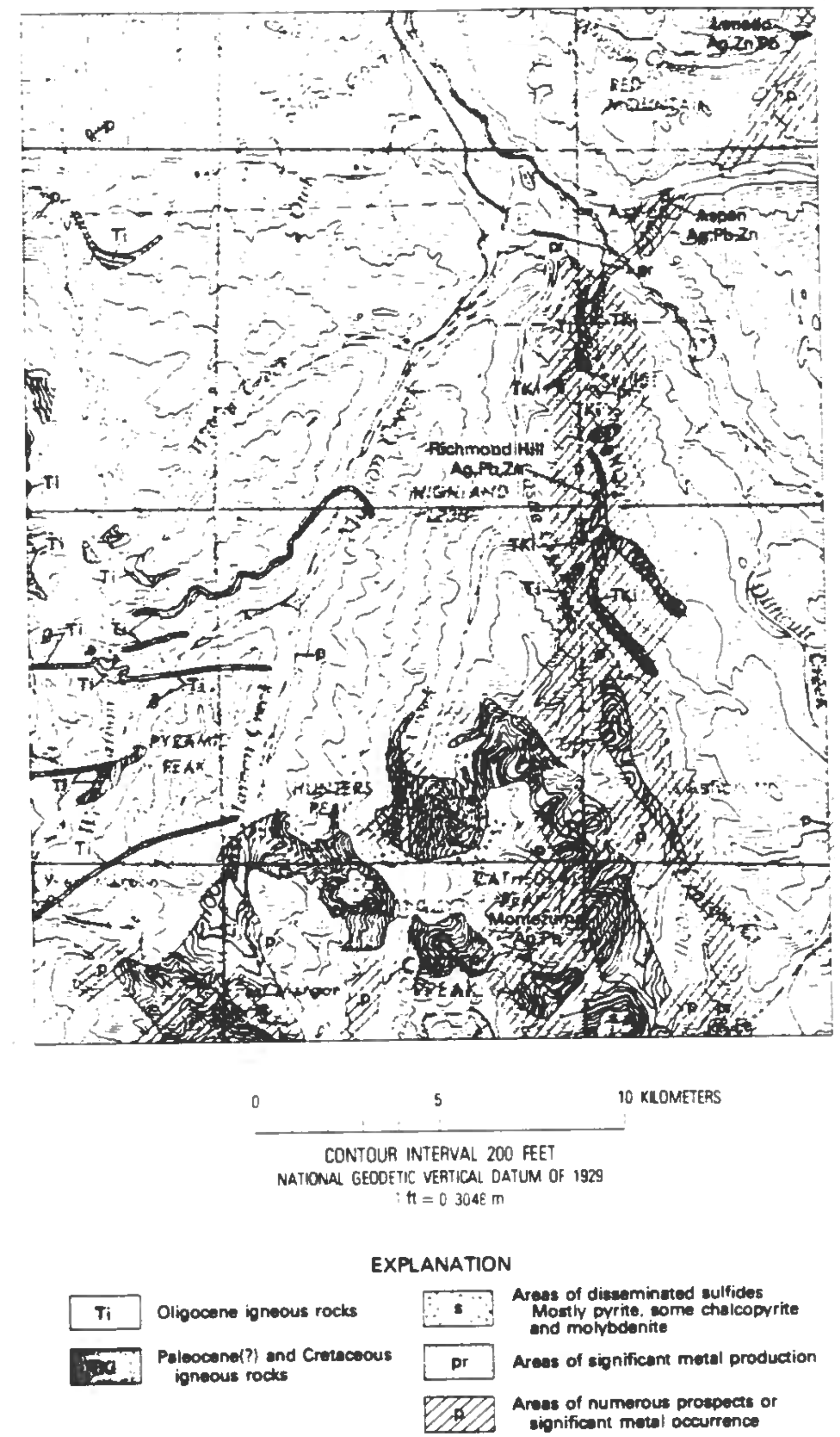


Fig. 5.—Areas of production, prospects, disseminated sulfides, and Oligocene and Laramide igneous rocks. Base from A.M.S. 1:250,000, Leadville, 1957.

Bryant, 1979

From last stop	Total	
		Smuggler Mountain is almost covered by moraine C (Bull Lake), and remnants of that moraine are visible on the lower part of the ski area. Post-glacial debris fans emerge from Spar, Vallejo, and Pioneer Gulchs and are potentially active.
		Return to Main Street, turn right and go two blocks, turn left and go one block, turn right and park on south side of Paepke Park. Lunch.

From last stop	Total	
		Colorado Highway 82 to Ashcroft. This route follows the trend of the Castle Creek fault zone south along the margin of the Sawatch uplift to the ghost town of Ashcroft near the junction of the Elk Mountains with the Sawatch Range.
		"The gorges or canons cut by Castle and Maroon Creeks and their branches are probably without a parallel of ruggedness, depth, and picturesque beauty in any portion of the west. The great variety of colors of the rocks, the remarkable and unique forms of the peaks, and the extreme ruggedness, all conspire to impress the beholder with wonder." Hayden (Hayden, 1876, p. 57).
.0	.0	Junction of Colorado Highway 82 and Castle Creek and Maroon Creek roads. Bear left on Castle Creek road. Roadcuts through moraine B which has been modified by erosion. Straight ahead, Precambrian quartz monzonite in fault slice across the Castle Creek fault zone.
.5	.5	Straight ahead, cliffs of Sawatch Quartzite and Manitou Dolomite on West Aspen Mountain.
.1	.6	Roadcut in moraine B on right.
.4	1.0	Entrance to Aspen Music School campus. Mine dump from Newman tunnel, which west to the ore zone on the east side of the Aspen Mountain syncline.
.2	1.2	Ahead, Maroon Formation on Highland Peak (3,774 m). Part of Highlands Ski Area visible to right of and below peak.
.2	1.4	Overturned beds near the top of the Maroon Formation. Most of the Maroon Formation and all the underlying Paleozoic formations are cut out by the Castle Creek fault here. Stratigraphic separation along fault estimated to be 4.3 km here.
.2	1.6	Ahead, upvalley view is of the ridge north of Hayden Peak. The ridge is composed of Oligocene granodiorite of the White Rock pluton.
.3	1.9	Moraine A on right.
.3	2.2	At 9:00 aplite porphyry of Late Cretaceous age on Aspen Mountain syncline caps skyline.

From last stop	Total	
.4	2.6	Queens Gulch road. Hill at 11:00 composed of steeply dipping Maroon Formation Valley to left of hill is in one of the few west-trending faults that cuts into the Maroon Formation from the margin of the Sawatch uplift. Spurr (1898) named it the Butte fault.
.4	3.0	Roadcut in debris fan.
.1	3.1	To left, Maroon Formation dipping steeply along the Castle Creek fault zone.
.1	3.2	Roadcut in morainal deposit.
.2	3.4	Cross Castle Creek.
.2	3.6	Exposures of Maroon Formation on valley side to right.
1.3	4.9	Mine dump of the Highland tunnel on left. This tunnel was extended 1.7 km beneath Richmond Hill during a mineral exploration project in the 1960's that attempted to intersect a downward extension of the orebody of the Midnight mine. Material on surface of dump is mostly black shale and limestone and white evaporite from the Belden Formation. Note the avalanche tracks on the lower part of the Conundrum Creek valley at about 1:00.
.2	5.1	Road to Conundrum Creek trail. Meadow on right was the site of Highland, a mining camp that flourished briefly from 1879 to 1881 while the immediately adjacent hills were intensively prospected.
.2	5.3	Roadcut in morainal deposit.
.1	5.4	Maroon Formation on left.
.4	5.8	Cut in Gothic Formation of Langenheim (1952). This is just above the portal of the Hope mine where several kilometers of tunnels were driven beneath Richmond Hill in the period from about 1910 to 1930. Little ore was found.
.3	6.1	STOP 8. Gothic Formation in roadcut. The Gothic Formation of Langenheim (1952) consists of predominantly gray clastic rocks below the red beds of the Maroon Formation and above the dark gray limestone, dolomite, and shale of the Belden Formation. South of the Elk Mountains and below

From last stop	Total	
		the Elk Range thrust the Gothic contains fossiliferous normal marine limestones of Des Moinsian age. North of the thrust no fossils have been found in the Aspen area, and the Gothic contains a few lenses of evaporite. Northwest of Aspen a transition into Eagle Valley Evaporite is inferred. In this exposure are calcareous sandstones and siltstones and sandy and silty limestones with obvious clastic mica. The presence of some grayish red beds suggests that these rocks are in the upper part of the Gothic. Current ripple marks on bedding planes and mudcracks at a nearby outcrop indicate deposition in shallow water subject to desication
.1	6.2	Gothic Formation forms cliffs for the next .3 mile on lower side to right; Maroon Formation forms cliffs above.
.3	6.5	Roadcut in debris fan.
.1	6.6	Little Annie road.
.2	6.8	Cliff of Gothic Formation at right.
.1	6.9	Roadcut in morainal deposit.
.2	7.1	Black shale of the Belden Formation in mine dump on left.
.1	7.2	Cut in debris fan. Avalanche tracks visible across creek at right.
.3	7.5	Dip slopes in lower Paleozoic rocks at the margin of the Sawatch uplift ahead.
.2	7.7	Raodcut in landslide deposit containing material from the Manitou Dolomite. The Manitou forms a dip slope high on the valley side.
.7	8.4	Belden Formation in dump to left.
.1	8.5	Talus from aplite of Late Cretaceous age.
.3	8.8	Cross Castle Creek. Ledges to right on lower part of valley side of Gothic Formation.
.2	9.0	On large debris fan derived from reworked morainal material present in tributary gully to west. To left, dip slope in Peerless Formation and Manitou Dolomite.

From last stop	Total	
.3	9.3	Straight ahead, Star Peak (4,121 m) composed of Oligocene granodiorite of the White Rock pluton.
.1	9.4	Elk Mountain Lodge and American Lake trail. Dip slope in Sawatch Quartzite and Peerless Formation at 9:00.
.2	9.6	Straight ahead is Express Creek valley, which trends parallel to the margin of the Sawatch uplift. Small cliffy knobs in that valley held up by Leadville Limestone.
.4	10.0	Leadville Limestone forms a dip slope on lower part of valley side on left.
.3	10.3	Ahead, Ashcroft Mountain (3,773 m). Dip slopes of of Sawatch Quartzite, Peerless Formation, and Manitou Dolomite form west slope.
.3	10.6	Toklat.
.1	10.7	Ghost town of Ashcroft. In the early 1880's Ashcroft was a thriving community rivaling Aspen in size. It is said to have had 2,500 inhabitants in 1885. By 1890 most of the business establishments had closed, although the post office operated until 1912 (Shoemaker, 1973). None of the mines in the vicinity had sufficient tonnages to sustain production for years. Some mines, such as the Montezuma, had a few years of very profitable production.
1.0	11.7	Crest of debris fan. View up valley of Pine Creek to right into White Rock pluton formed by Oligocene granodiorite.
1.0	12.7	STOP 9. Junction of Pearl Pass road with road to iron mine. Close to the geographic and geologic joint between the Elk Mountains and the Sawatch Range. South at head of the valley is Star Peak (4,121 m) composed of Oligocene granodiorite of the White Rock pluton, which has a K-Ar age on biotite of 34 m.y. (Obradovich and others, 1969).

The lower valley sides here are areas of Gothic formation showing through the cover of morainal debris. Higher up on the west side of the valley granodiorite of the White Rock pluton crops out over 600 vertical meters. It is capped by hornfels derived by contact metamorphism of the Maroon

From last stop	Total

Formation grading up into unmetamorphosed Maroon on the very crest of the ridge about 200 m above the granodiorite.

By the east edge of the valley bottom is a pile of rusty weathered iron ore from an open pit mine in a contact metasomatic iron deposit in limestone of the Belden Formation near the contact of the White Rock pluton (fig. 5). The mine is at 3660 m altitude and can only be worked in the summer months. Ore is trucked down to the valley bottom where it is loaded in larger trucks and taken to the railroad at Woody Creek. This mine has been operating for 18 years.

The road to the right leads to Pearl Pass and Crested Butte (a rough jeep road open only a short period in late summer), and a branch leads to the Montezuma mine at 3,877 m altitude. The Montezuma was the richest mine near Ashcroft and produced very rich near-surface ore shortly after its discovery in 1881 and was owned by H.A.W. Tabor at one time.

Subsequently, unoxidized ore was mined and milled on a small scale, and small amounts of ore were shipped as recently as the early 1960's.

Turn around and return to Ashcroft.

STOP 10 (Optional). A few of the buildings of the former boom town of Ashcroft were still standing 90 years after its heyday, and in 1976 as a Centennial project under the auspices of the Aspen Historical Society they were stabilized. Time permitting (we want to give you a little time in which to wander around the second time around the boom town of Aspen before dark) we will stop and look at the remains of Ashcroft.

From last stop	Total	
		Sunday, October 3. Colorado Highway 82 to Maroon Lake. A drive up a spectacular glacial trough cut in red beds of the Maroon Formation to the famous view of the Maroon Bells across Maroon Lake. Although the canyon is the type locality of the Maroon Formation, few outcrops occur at road level. Debris fans, talus, and colluvium cover the lower sides of the valley.
.0	.0	Junction of Colorado Highway 82 with Castle Creek and Maroon Creek roads. Bear right on Maroon Creek road. Enter area of moraine B.
.2	.2	Ahead, Mancos Shale underlies Buttermilk Ski Area.
.5	.7	Cliff of Chinle Formation ahead. Prominent surfaces on cliff are joints parallel to a nearby fault; bedding dips north towards observer.
.3	1.0	Trail to Snowmass-at-Aspen leaves road, starts at park on right.
.1	1.1	On right, Morrison Formation is exposed in canyon of Maroon Creek.
.2	1.3	On right, Entrada Sandstone and Chinle Fromation are exposed in canyon of Maroon Creek.
.1	1.4	Highlands Ski Area. Much of this ski area is on a dip slope in the State Bridge Formation. To right, across Maroon Creek, is a section from the Chinle Formation to the Dakota Sandstone.
.2	1.6	To right, orange sandstone is Sloane Peak Member of the State Bridge Formation, which is cut out to the west along the valley side by the pre-Chinle unconformity.
.2	1.8	Cut to left is in State Bridge Formation; on slope ahead is Sloane Peak Member of the State Bridge Formation.
.5	2.2	Cross Maroon Creek.
.2	2.4	Cut in morainal deposit of Pinedale age; to left across creek are exposures of State Bridge Formation.
.2	2.6	Pyramid Peak (4,273 m) ahead; to right are cliffs of Maroon Formation and State Bridge Formation. Above are Chinle Formation, Entrada Sandstone, and Morrison Formation.

From last stop	Total	
.8	3.4	Cross Willow Creek.
.2	3.6	View of Pyramid Peak ahead; left of it is canyon of East Maroon Creek.
.4	4.0	To left, cliffs of Maroon Formation.
.4	4.4	Avalanche track from Highland Peak on left.
.4	4.8	Avalanche track from Highland Peak on left.
.4	5.2	Avalanche track on right.
.4	5.6	Cirque and hanging valley to left; morainal deposit at and below its lip.
.2	5.8	Avalanche track on right with wood brought down last winter.
.4	6.2	Sill of gray porphyritic granodiorite in red beds of the Maroon Formation on left. This is the same sill visible north of and 400 m above Maroon Lake.
.7	6.9	Roadcut in Maroon Formation on right.
.5	7.4	Hanging valley on left.
.4	7.8	View up East Maroon Creek to left. Heavily wooded ridge between the two forks of Maroon Creek is mantled by morainal deposits. The road is on debris fans composed of morainal material and bedrock debris from the steep valley wall.
.4	8.2	Roadcut in sandstone in the Maroon Formation.
.3	8.5	Debris fan from major hanging valley to right.
.4	8.9	Maroon Formation crops out at road level on right.
.8	9.7	Maroon Lake. STOP 11. Up valley across Maroon Lake, the Maroon Bells (North Maroon Peak, 4,271 m; and Maroon Peak, 4,315 m) are composed of red beds of the Maroon Formation. The rocks on the lower slopes have been altered by heat from Oligocene intrusive rock below the valley bottom and subsequently have been changed to shades of dark-grayis-red and gray. A large rock glacier beneath the north face of North Maroon Peak was moving downslope at the rate of about 60 cm a year in the middle 1960's (Bryant, 1971). The gentle rocky

From last stop	Total	
		deposit blocking the valley between Maroon Lake and the Maroon Bells is a lanslide mostly composed of somewhat metamorphosed Maroon Formation which is exposed on the south side of the valley. South and west of Maroon Lake, east-trending dikes of porphyritic granodiorite cut the Maroon Formation. Southeast of Maroon Lake, the front of an active-appearing rock glacier is the source for much talus. Just west to the active front, part of the rock glacier appears to be inactive. The Maroon Lake campground lies on a large debris fan heading in a steep gully in red beds north of the lake. Sills of gray granodiorite are obvious in the red beds on that slope, and they are offset along a fault in the gully. The debris fan forms a dam which holds back the waters of Maroon Lake. A short and popular walk is from Maroon Lake up valley to Crater Lake, from which an excellent closeup view of the Maroon Bells can be enjoyed.
		Return to Highway 82 and go northwest to the junction of Colorado 133, turn left.
.0	.0	Intersection with Colorado 133, turn left.
.1	.1	Cross Roaring Fork River.
.4	.5	Railroad crossing.
.5	1.0	Downtown Carbondale to left. To the right Eagle Valley Formation and overlying terrace gravels are exposed in streamcut banks.
1.0	2.0	Four terrace levels visible here.
.1	2.1	Mancos Shale in hills ahead marks the west end of the Roaring Fork syncline.
.9	3.0	Cross Crystal River.
1.0	4.0	If the light is right, one can see the rock glaciers on the north and northwest sides of Mt. Sopris.
1.6	5.6	At 2:00 the red exposure if Maroon Formation. Near Mt. Sopris the beds beneath the Maroon Formation have been considered by some workers to be Gothic Formation, which contains a few gypsum beds, and to be Eagle Valley Formation by others. The Gothic-Maroon contact is placed at the color from mostly brown, gray, and green rocks below to mostly reddish-brown rocks above.

From last stop	Total	
.3	5.9	Cross Thompson Creek. The Thompsom Creek valley was followed by the Aspen and Western Railway Company's line to coal mines in the lower part of the Mesaverde Formation near Willow Park. Only one trainload of coal is known to have been hauled on this railroad, that was in 1888. About 4 miles west of the highway, the highway, the Gothic Formation is exposed in the core of a north-trending anti-cline. West of the anticline the rocks dip into the Piceance Basin.
.4	6.3	Outcrops of Maroon Formation containing many beds of conglomeratic coarse-grained sandstone.
.1	6.4	Across the river a poorly exposed section of Mancos Shale, Dakota Sandstone, Morrison Formation, Entrada Sandstone, and Maroon Formation dips north away from the Sopris pluton and into the Roaring Fork syncline. A well-exposed section is present on Potato Bill Creek.
.5	6.9	Road to left crossing Crystal River leads to Potato Bill Creek. Je on PPm
.4	7.3	Outcrop of conglomeratic Maroon Formation.
.9	8.2	Maroon Formation outcrop.
.8	9.0	Across the river the old railroad grade of the Crystal River and San Juan Railway is visible. The town of Marble was connected to Carbondate by rail in 1906, although Redstone and Coal Basin had rail service as early as 1900. The CR & SJ railroad was abandoned in 1941.
.7	9.7	Maroon Formation to the left.
.2	9.9	To the left, the slabs of white marble lying along the railroad grade are waste blocks which were used as riprap. To the right are outcrops of Maroon Formation.
1.1	11.0	Ahead, outcrops along skyline on the right side of the river are Maroon Formation.
.5	11.5	To the left, Avalanche Creek road junction. View of Bulldog Creek that has eroded its valley at the contact of the Sopris pluton and upturned Gothic Formation. At 4:00, good view of transition beds at the Gothic-Maroon contact.

From last stop	Total	
		"On the 29th a rain-storm had set in, and everything was now wet, thoroughly saturated. Muddy torrents poured down the upper slopes and dashed over the cliffs into the valley. Avalanches of wet earth carrying rocks and trees formed near the summits and came roaring down, discharging great masses of debris into the river, and tearing out such gorges in the alluvial bottoms to make travel almost impossible." (Holmes, 1876, p. 63-64 in Crystal River valley, then called Rock Creek, near its junction with Avalanche Creek in 1874 field season).
.6	12.1	To the left, Gothic Formation.
.2	12.3	STOP 12 (Optional). Outcrops of granodiorite. At the level of exposure this stock is separate from the Sopris pluton but may be connected with it at depth. The Mt. Sopris pluton is the northernmost of numerous mid-Tertiary plutons exposed in the Elk Mountains and has concordant biotite K-Ar and zircon fission-track ages of 34 m.y. (Cunningham, Naeser, and Marvin, 1977).
.3	12.6	View ahead of Maroon Formation at the skyline.
.4	13.0	South edge of the granodiorite stock.
.4	13.4	To the left at river level is Penny Hot Springs site. At 8:00, Gothic and overlying Maroon Formations upwarped against granodiorite. To the right, from 3:00 to 5:00, is the apparent concordant top of the stock.
.1	13.5	Exposures in the high cliffs to the west are southward-dipping Maroon Formation.
.2	13.7	Distant mountain ahead is Chair Mountain (3,888 m), a glacial-carved portion of the Ragged Mountain laccolith. The laccolith is mapped as quartz monzonite porphyry (Godwin, 1968) and is considered Oligocene in age by Obradovich and others (1969).
.3	14.0	Coming into view on right in the high cliffs are outcrops of Maroon Formation that consist of sandstone, conglomeratic sandstone, and conglomerate beds with little, if any, siltstone and claystone. This part of the Maroon Formation is thought to have been deposited in the headward part of the fluvial system, perhaps as alluvial fans.

From last stop	Total	
.9	14.9	Very large boulders such as those seen at creek level are common along this stretch of the Crystal River. They result from rock falls made possible by oversteepening of the canyon walls during the Pleistocene.
.6	15.5	Outcrops of Maroon Formation, note the coarse-grained sandstone and conglomerate and the crossbedding.
.4	15.9	Ahead at 1:00, the drag fold with beds of the Entrada Sandstone and overlying Morrison Formation is on the downthrown (east) side of a north-trending fault; Maroon Formation is on the west side of the fault.
.3	16.2	The town of Redstone is across the river.
.3	16.5	Road crosses Coal Creek.
.2	16.7	STOP 13 (Optional). Beehive ovens were used for coking coal. Two hundred ovens, in two rows, were in operation when the coal basin mine shut down in 1909 (McCoy and Collman, 1972). View to thewest is of the fault that downdrops Entrada and Morrison on the east side. View up the valley is of Chair Mountain (3,888 m) formed by mid-Tertiary prophyritic granodiorite of the Ragged Mountain laccolith. Across the river is an outcrop of crossbedded sandstone and pebble to cobble conglomerate of the Maroon Formation containing a variety of clasts from the Precambrian core of the Uncompahgre Uplift.
		Valley entering from the west is that of Coal Creek, which drains Coal Basin, the site of 5 mines of the Mid-Continent Coal and Coke Company. Coal Basin is a topographic feature eroded in Mancos Shale that has been domed above an intrusive of probable mid-Tertiary age. The steep Mancos and Mesaverde slopes above the basin are the sites of frequent mudflows.
.2	16.9	Exposures to the right reveal the top of the Maroon Formation, the Entrada Sandstone, and the Morrison Formation. Not visible from the road, but mapped by Donnell (1962), is a light-gray sandstone that he considered to be a south-eastern tongue of Permian age of the Weber Sandstone (Donnell, 1954). It is considered by Poole and Shropshire (1969) to be the Gartra Member at the base of the Chinle Formation.

Maroon becomes v [illegible]

From last stop	Total	
.6	17.5	At the top of the hill to the right is the ledge-forming Dakota Sandstone.
.2	17.7	Roadcut exposure of a conglomerate in the Maroon Formation.
.2	17.9	Light-greenish-gray bed in the Maroon Formation.
.4	18.3	Outcrops of the Maroon Formation on both sides of the road.
.2	18.5	The road is in the light-colored Maroon sandstone.
.4	18.9	Road crosses the Crystal River.
.6	19.5	At 1:00, Mesaverde Group.
.1	19.6	We are crossing through a poorly exposed section that includes the top of the Maroon Formation, the Entrada Sandstone, the Morrison Formation, the Dakota Sandstone, and a bit of the Mancos Shale. A fault within the Mancos is considered to be the northwest extension of the Elk Mountain thrust. The top of the Mancos and the Mesaverde Group are present south of the fault.
.1	19.7	Road crosses Crystal River. Upper part of the Mancos Shale exposed in stream cut to the right.
.1	19.8	Roadcut exposure of fine-grained sandstone in the lower part of the Mesaverde Group.
.2	20.0	Exposure of gray shale above the basal Mesa-verde Group.
.2	20.2	Holgate mine and dump at 11:00. The Placita mine on right side of the road is not as visible. Both produced coking coal.
.2	20.4	Placita townsite.
.1	20.5	Holgate mine now at 9:00.
.1	20.6	On our right is the old McClure Pass Road. Ahead are large roadcuts along the new McClure Pass road, with excellent exposures of Mesaverde Group.
		Looking up the Crystal River, one sees Chair Mountain rising above outcrops of Mesaverde Group. The Ragged Mountain laccolith has an intrusive contact with indurated upper Mancos Shale.

From last stop	Total	
.9	21.5	Gunnison County line.
.1	21.6	Road intersection; turn left. Highway 133 continues across McClure Pass to Somerset or Crested Butte. Field trip follows road to Marble. Ahead is Raspberry Creek phacolith composed of quartz monzonite porphyry. On the left is poorly exposed Mesaverde Group overlain by moraine deposits and undifferentiated gravels.
.5	22.1	Roadcuts in alluvial fan.
.8	22.9	Coming into sight, at the head of the valley, is part of the Treasure Mountain dome, with Paleozoic beds dipping to the west away from the dome.
1.3	24.2	At the head of the valley is Whitehouse Mountain, beds of Gothic, Entrada, and Morrison Formations dip northwest (toward us) off the dome.
.1	24.3	Dump to the right is from the Genter coal mine.
.1	24.4	Cross Crystal River.
.3	24.7	Roadcut exposure of Mesaverde Group.
.6	25.3	Marble cemetery to the left.
.5	25.8	On the right is the Marble airport.
.1	25.9	Talus to the left is from a sill of quartz monzonite porphyry.
.1	26.0	Now visible at the head of the valley is Sheep Mountain capped by basal Mancos dipping north off the Treasure Mountain dome. The Crystal River canyon is to the right of Sheep Mountain.
.6	26.6	Slate Creek. Road crosses debris from the latest of many mudflows. The debris is derived from Mancos Shale and Measaverde Group. The low hills to the left are part of a landslide deposits. Outcrops of Mancos and basal Mesaverde are seen above the landslide.
.1	26.7	The scattered blocks of marble are left over from marble production in the area. The finishing mill was located between Slate Creek and Carbonate Creek and between the road and the Crystal River.

From last stop	Total	
4.	27.1	City limit sign, Marble, Colorado.
.5	27.6	Historic church on left.
.1	27.7	STOP 14. Walk east to Carbonate Creek crossing.

Mudflows are a common occurrence here; a big one in 1941 destroyed many buildings. Looking up Carbonate Creek one sees the lower exposure of Mancos Shale, a landslide to the left, and further left, faulted Mancos and Mesaverde Formations on the face of Gallo Hill. The skyline to the right of Gallo Hill is underlain by Oligocene granodiorite of the Snowmass pluton. The Elk Range thrust is locally preserved along the base of the high mountains, where it separated Pennsylvanian from Cretaceous rocks.

To the east is the north flank of the Treasure Mountain dome. This dome was formed about 12 m.y. ago by intrusion of a pluton of soda granite (Obradovich and others, 1969). Pre-cambrian rocks are exposed in the core of the dome. The pre-Entrada unconformity, which cuts across Pennsylvanian to Cambrian rocks from northeast to southwest towards the Uncompahgre uplift, is exposed on the flanks of the Treasure Mountain dome. Locally, heat from the pluton has metamorphosed the rocks below the Mancos Shale.

To the right, Yule Creek flows northward along the west edge of the dome. Fine-quality white marble derived by contact metamorphism of the Leadville Limestone was quarried along Yule Creek and used in the Lincoln Memorial. The heyday of marble production was about 1910 when the industry is reported to have supported a population of 3,000 in the area. Intermittent production continued until 1941 (McCoy and Collman, 1972).

Lunch. Return to Denver.

References

Bass, N.W., and Northrop, S.A., 1950, South Canyon Creek Dolomite Member, a unit of Phosphoria age in Maroon Formation near Glenwood Springs, Colorado: Amer. Assoc. of Petrol. Geol. Bull., v. 34, n. 7, p. 1540-1551.

Bass, N.W., 1963, Geology of Glenwood Springs quadrangle and vicinity, northwestern Colorado: U.S.G.S. Bull. 1142-J, 74 p.

Bryant, Bruce, 1971, Movement measurements on two rock glaciers in the eastern Elk Mountains, Colorado: in Geological Survey Research 1971: U.S.G.S. Prof. Paper 750-B, p. B108-B-116.

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

Cunningham, C.G., Naeser, C.W., and Marvin, R.F., 1977, New ages for intrusive rocks in the Colorado mineral belt: U.S.G.S. Open File Report 77-573, 7 p.

Donnell, J.R., 1954, Tongue of Weber Sandstone in Maroon Formation near Carbondale and Redstone, northwestern Colorado: Amer. Assoc. of Petrol. Geol. Bull., v. 38, n. 8, p. 1817-1821.

Donnell, J.R., 1962, Geologic map and reserve estimates, Carbondale coal field, Colorado: U.S.G.S. Open-File Report.

Freeman, V.L., and Bryant, Bruce, 1977, Road logs for Rocky Mountain Association of Geologists Snowmass Conference September 29-30, 1977, in Veal, H.K., Ed., Exploration Frontier of the Central and Southern Rockies: Rocky Mountain Association of Geologists, Denver, p. 469-495.

Gale, H.S., 1910, Coal fields of northwestern Colorado and northeastern Utah: U.S.G.S. Bull. 415, 265 p.

Godwin, L.H., 1968, Geologic map of the Chair Mountain quadrangle, Gunnison and Pitkin Counties, Coloraod: U.S.G.S. Geologic Quadrangle Map GQ 704.

Hayden, F.V., 1976, General view of the geography and geology of the Elk Mountains-Eruptive granites-Rhyolites and dikes-Erosion on a grand scale-Local drift deposits, Chapter 5, in Geology, mineralogy, and mining industry: U.S. Geol. and Geog. Surv. of the Territories (8th) Annual Report (Hayden), p. 54-58.

Holmes, W.H., 1976, Report on the geology of the northwestern portion of the Elk Range, Chapter 6, in Geology, mineralogy, and mining industry: U.S. Geol. and Geor. Surv. of the Territories (8th) Annual Report (Hayden), p. 59-71.

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

Langenheim, R.L., Jr., 1952, Pennsylvanian and Permian stratigraphy in Crested Butte quadrangle: Amer. Assoc. of Petrol. Geol. Bull, v. 36, p. 543-574.

Larson, E.E., Bradley, W.C., andOzima, Minoru, 1975, Late Cenezoic basic volcanism in northwestern Colorado and its implications concerning tectonism and the origin of the Colorado River system, in Curtis, B.F., Ed., Cenezoic History of the Southern Rocky Mountains: GSA Memoir 144, p. 155-178.

McCoy, Dell, and Collman, Russ, 1972, The Crystal River Pictoral: Denver, Sundance Ltd., 225 p.

Mallory, W.W., 1966, Cattle Creek anticline, a salt diapir near Glenwood Springs, Colorado, in Geological Survey Research 1966: U.S.G.S. Prof. Paper 550-B, p. B12-B15.

Murray, F.N., 1969, Flexural slip as indicated by faulted lava flows along the Grand Hogback monocline, Colorado: Journal of Geology, v. 77, n. 3, p. 333-339.

Obradovich, J.D., and Cobban, W.A., 1975, A time scale for the Late Cretaceous of the western interior of North America, in Caldwell, W.G.E., Ed., The Cretaceous System of the Western Interior of North America: Canada Geological Association Special Paper 13, p. 31-54.

Obradovich, J.D., Mutschler, F.E., and Bryant, Bruce, Potassium-argon ages bearing on the igneous and tectonic history of the Elk Mountains and vicinity, Colorado - A preliminary report: GSA Bull., v. 80, n. 9, p. 1749-1756.

Piety, L.A., 1981, Relative dating of terrace deposits and tills in the Roaring Fork valley, Colorado: Univ. of Colorado unpubl. M.S. Thesis, 209 p.

Poole, F.G., and Shropshire, K.L., 1969, Gartra Member of the Chinle Formation (Upper Triassic) south of Glenwood Springs, western Colorado: GSA Abstracts with Programs for 1969, pt. 5, p. 65-66.

Shoemaker, Len, 1973, Roaring Fork Valley, 3rd Edition (Revised): Denver, Sundance, Ltd., 216 p.

Spurr, J.E., 1968, Geology of the Aspen mining district: U.S.G.S. Monograph 31, 260 p.

Yeend, W.E., 1969, Quaternary geology of the Grand and Battlement Meas area, Colorado: U.S.G.S. Prof. Paper 617, 50 p.

Young, R.G., Keighin, C.W., and Campbell, J.A., 1981, Road log from Grand Junction to Glenwood Canyon and return to Grand Junction, in Epis, R.C., and Callender, J.E., Eds., Western Slope Colorado: New Mexico Geological Society, p. 17-28.

TECTONIC HISTORY OF WEST-CENTRAL COLORADO

by
Ogden Tweto[1]

ABSTRACT

West-central Colorado provides a record of major tectonic events dating from the Precambrian to the Quaternary. Fault systems of regional extent that originated in Precambrian time were repeatedly reactivated, exercising a profound control on many elements of structure and sedimentation through later time. Numerous unconformities in the pre-Pennsylvanian Paleozoic rocks document repeated local tectonism superposed on the broad patterns of regional epeirogenic movements. Major highlands — elements of the Ancestral Rocky Mountains — rose in the northeastern and southwestern parts of the area in the Early Pennsylvanian and underwent repeated movements until the Late Triassic. Thick upper Paleozoic sediments in the trough between the uplifts consist in part of an evaporite facies. Flowage in areas of thick evaporites began as early as Late Permian time and strongly affected Permian and Triassic sedimentation as well as later structure. A pre-Middle Jurassic (pre-Entrada) unconformity bevels the region and was followed by pre-Morrison fault movements. Laramide orogeny in this part of Colorado began with the elevation of the generally anticlinal Sawatch Range, largely within the late Paleozoic depositional trough. Re-elevation of the old Pennsylvanian positive units followed shortly, and elevation of the domal White River uplift followed later in Laramide time. Concurrently with early Laramide uplift, a large new sedimentary basin developed to the west. This, the Piceance basin, has its axis high on the western flank of the preceding late Paleozoic basin. Concurrently also with early Laramide uplift, igneous intrusive and volcanic activity began in the area of the Colorado mineral belt, which exends across the southeastern part of the area. In Oligocene time the igneous activity became more widespread. In Miocene time, rifting or block faulting and basaltic volcanism related to crustal extension occurred. Orogenic sediments accumulated concurrently, largely in grabens along the trend of the Rio Grande rift system. Still later, some of these sediments and the basalts were deformed by folding and faulting, differentially elevated as a result of renewed uplift of mountain units, or subsided as a result of both flowage and dissolution of evaporites.

INTRODUCTION

Major events in the lengthy tectonic history of west-central Colorado are briefly reviewed and collated in this article. In a region so dominated by Laramide and younger tectonic features, earlier tectonic events and the control they exerted over younger features and events tend to be overlooked. Here emphasis is placed on the antiquity and prolonged influence of some structural features and on the effects of flowage or diapirism of evaporites on subsequent sedimentation and structure.

The two maps in this article (Plate 1 in pocket, and Fig. 1) correspond to the Leadville 1° x 2° quadrangle, a map of which is available in preliminary form (Tweto and others, 1976). This map documents many statements made in the following text, though for brevity, only infrequent reference to it is made. The rock units that constitute the framework for discussion of tectonics are listed in Table 1 along with pertinent information on distribution and stratigraphic relations. The units themselves are not described; information concerning them is available in referenced publications. In the interest of brevity, references are held to a minimum in this article, though they are nonetheless fairly numerous. The references cited will lead to many others, particularly for maps.

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PRECAMBRIAN FRACTURE SYSTEMS

Two major Precambrian fracture systems exposed in west-central Colorado affected or controlled many younger tectonic features. One system, of northeast trend, consists of the Homestake shear zone in the Sawatch Range and faulted extensions northeastward in the Gore Range and into the Front Range (Plate 1). The other system, of north-northwest trend, is part of a wide belt of fracturing that extends at least 300 km through the mountains of Colorado and probably farther in the subsurface. Faults of this belt border both sides of the Gore Range and extend through the part of the Front Range considered here.

The Homestake shear zone (Tweto and Sims, 1963; Tweto, 1974) consists of many individual shear zones in a belt 10 km wide. It is best developed and most studied on the eastern flank of the Sawatch Range. On the basis of present knowledge, it passes to the southwest into a complex fault of the same trend (Plate 1), though much of that part of the range has not been mapped in detail. The Homestake shear zone is characterized by a wide variety of cataclastic rocks, ranging from blastomylonite gneisses down to gouge and indicating differing environments of formation and, hence, recurrent movements through a protracted period of time. Some of the individual shear zones are at least as old as a granite of ~ 1,400 m.y. age; others are geologically of somewhat younger Precambrian age. Some were reactivated in Phanerozoic time, as indicated by the degradation of cataclastic gneisses and mylonites to gouge and breccia, and some were not. The main Precambrian movements on the shear zone were evidently left-lateral strike-slip, though movements of other types and directions occurred through later time. The total displacement along the Homestake zone as a whole is unknown but may have been large. Different assemblages of gneisses and granites are present on the two sides in both the Sawatch and Gore Ranges. The bight in the late Paleozoic Front Range highland — where the western border left the Gore fault and swung eastward into South Park (Fig. 1 and Plate 1) — corresponds closely with the shear zone. Changes in thickness of some Paleozoic formations across the shear zone suggest minor, possibly vertical movements in pre-Pennsylvanian Paleozoic time. The shear zone approximately borders the northwest side of the Colorado mineral belt in the area under consideration here. Gravity, magnetic, and geologic data (Behrendt and Bajwa, 1972; Tweto and Case, 1972; Isaacson and Smithson, 1976) suggest that it influenced the trend of a batholith that is inferred to underlie the mineral belt, just as a longer system of echelon shear zones seem to have influenced location and trend of the mineral belt as a whole (Tweto and Sims, 1963).

Precambrian faults of the second or north-northwest-trending system account for much, if not all, of the north-northwest "grain" so prominent in the topography and geology of the mountain province of Colorado. These faults have a long history of recurrent movements of various types, and parts of some of them are literally active today. One major fault of the system, the Ilse, in the Wet Mountains southwest of Pueblo, Colo., predates the oldest (1,700 m.y.) Precambrian granite in Colorado (R. B. Taylor, oral commun., 1973). In the area of the Gore and western Front Ranges, however, the faults seem to postdate the Homestake shear zone.

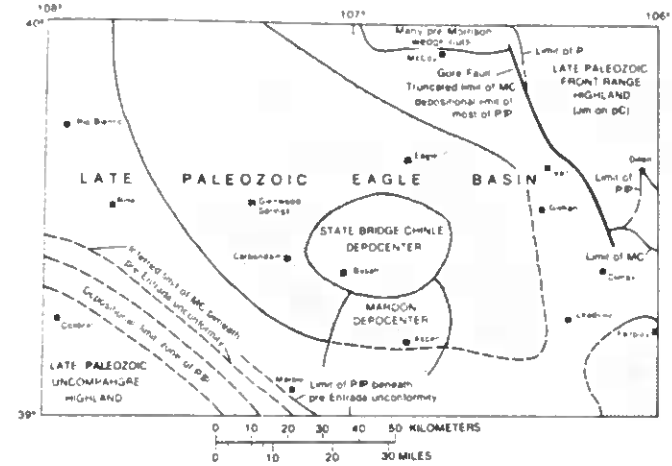

Fig. 1 — Major paleotectonic features in west-central Colorado. Principal areas of Pennsylvanian evaporite deposition are in coarse dot pattern and are inferred where boundaries are dashed. Jm, Morrison Formation; P, Permian; PIP, Permian and Pennsylvanian; MC, Mississippian through Cambrian; pC, Precambrian.

The Gore fault, along the western side of the Gore Range (Plate 1), is one of the most significant faults of the north-northwest system. This fault, which near the Colorado River is intruded by a dike of 1,000 m.y. age (Barclay, 1968), formed a segment of the western border of the late Paleozoic Front Range highland (Plate 1). As discussed in following sections, it was also active during the pre-Pennsylvanian Paleozoic, the early Mesozoic, the Laramide orogeny, and the late Tertiary. On the east side of the fault, the Morrison Formation lies on Precambrian rocks, and on the west side, 3,000 m of sedimentary rocks lie between the Morrison and the Precambrian.

The history of other faults of the north-northwest system is not as well documented as that of the Gore fault, for lack of stratigraphic record. The Blue River fault, on the east side of the Gore Range (Plate 1) — previously called the Frontal fault (Tweto and others, 1970) — is a complex fault zone consisting of displaced segments of a Precambrian fault zone connected in zigzag pattern by faults of probable Laramide and Tertiary ages. The Precambrian elements are broad shear zones and mylonitic rocks. The fault along the eastern side of the Williams Fork graben (Plate 1) is part of a lengthy system of north-northwest-trending faults on the western flank of the Front Range. These faults are in part shear zones of Precambrian character and are inferred to be reactivated fractures along a

Precambrian fault zone. Similarly, the north-northwest trend of the faults of the Arkansas Valley graben (Plate 1) suggests inheritance from Precambrian faults, though evidence of Precambrian origin of the faults is thus far lacking. Many other major structural features have north-northwest trends that, considered in light of the known Precambrian origin of the Gore and Blue River faults, suggest control by old faults in the basement. Examples are the Williams Range thrust fault, the London and Weston faults, the Castle Creek fault, parts of the Grand Hogback, and perhaps even the basement trough of the Piceance basin (Plate 1).

PRE-PENNSYLVANIAN UNCONFORMITIES

Numerous unconformities are present in the sequence of Cambrian, Ordovician, Devonian, and Mississippian rocks (Table 1). All can be broadly correlated with widely recognized regional epeirogenic events, but in this area, at an apparent crest in the Paleozoic North American craton, the effects of epeirogeny are magnified, and some evidence of local differential uplifts exists. The unconformities were first appraised by Lovering and Johnson (1933) who concluded from them that a persistent landmass existed in the area of the present Front Range through all of Paleozoic and most of Mesozoic time. This conclusion was based on the distribution of rocks as presently preserved, largely without regard to their original extent and the cumulative effects of overlapping unconformities, and it is no longer tenable in such sweeping form. Nevertheless, there are strong suggestions of local uplift at times in the area of the Gore and Tenmile Ranges (a part of the highland visualized by Lovering and Johnson), particularly in the Late Cambrian and Late Devonian.

The Sawatch Quartzite thins rapidly from about 60 m at the Eagle River near Gilman to about 30 m at the Gore fault, where it is markedly conglomeratic at a locality where it is fully preserved beneath the Peerless Formation (Tweto and Lovering, 1977). This suggests a "high" in the vicinity of the Gore Range in Late Cambrian time, though paleogeographic data are severely limited. In this area, as in many others in Colorado, the Cambrian rocks have been so widely eroded beneath overlapping unconformities that their original extent only can be speculated upon. Moreover, Cambrian time was not one of geologic calm in Colorado. Sizable alkalic-mafic intrusive bodies and long diabase dikes in south-central and western Colorado are of Early to Late Cambrian age (Parker and Sharp, 1970; Hansen, 1971; Olson and others, 1977). These areas were almost certainly sites of uplift and nondeposition.

A pre-Manitou unconformity records uplift and widespread erosion of Cambrian rocks throughout the region, except in the area of the White River uplift (Bass and Northrop, 1963), where the Cambrian sequence is thickest and probably complete. Near the Mosquito fault in the Tenmile Range, north of Climax, Cambrian rocks were removed entirely, and the Manitou Dolomite lies on Precambrian rocks just as it does in extensive areas in south-central Colorado. Erosion that produced a pre-Harding unconformity irregularly reduced the Manitou Dolomite and removed it completely in at least the area from near Tennessee Pass to the north end of the Sawatch Range, where the Harding Sandstone lies on the Peerless Formation. Erosion that produced a pre-Fremont unconformity reduced the Harding Sandstone to as little as 1 m at Treasure Mountain south of Marble (Mutschler, 1970; Gaskill and Godwin, 1966) and probably removed it entirely in many areas, though this cannot be proved in the absence of the Fremont Limestone. The lengthy time values of the Ordovician unconformities are illustrated in a recent report by Ross (1976, Fig. 3). The unconformities reflect epeirogenesis on nearly a continental scale, but the details indicate superposed, gentle tectonic warping in this part of Colorado. South of Red Cliff (Plate 1), for example, the Harding and underlying Peerless are in slight angular disconcordance, and the Harding fills steep-sided channels cut as much as 6 m into the Peerless (Tweto, 1949).

A pre-Parting unconformity marks a great hiatus from the Late Ordovician to the Late Devonian. Erosion that preceded deposition of the Upper Devonian Parting Formation destroyed the record of earlier Paleozoic events much more widely than the earlier erosional episodes. Regionally, the Parting truncates all formations from the Ordovician Fremont down to the Precambrian. Mild tectonism is recorded both by the unconformity and by the Parting Formation. South of Red Cliff, the Parting and Harding are in angular discordance of as much as 6°, and a discordance of 2° was measured in mine workings at Gilman (Tweto and Lovering, 1977). The conglomerate content and pebble size in the Parting increase progressively northeastward to the Gore fault. In some fault blocks of this fault zone, the Parting lies on Cambrian rocks, overstepping from Peerless to Sawatch, and in other blocks it lies on Precambrian rocks (Tweto and Lovering, 1977). These relations strongly suggest pre-Parting, presumably Devonian, movements along the Gore fault, and the change northeastward to coarse facies near the fault suggests a sediment source at the site of the Gore Range or vicinity. Campbell (1967) deduced eastern and northern sources for the Parting as exposed from Gilman northwestward into the White River uplift, and Singewald (1931) noted an area of nondeposition in the Mosquito Range near Alma. To the west, in the Sawatch Range, Elk Mountains, and White River uplift, the Parting is irregular in thickness, due in part to an uneven floor. It is locally micaceous and even arkosic (Johnson, 1944; Bass and Northrop, 1963), but no direct evidence of closely associated tectonism or of local sources has been noted.

An unconformity at the base of the Gilman Sandstone marks

Table 1.-Principal rock units in west-central Colorado
[Units marked by * are eastern units that have western equivalents marked by **.
Thicknesses and remarks apply to area covered in Plate 1.]

Age	Formation or unit	Maximum thickness Meters	Feet	Remarks
Quaternary	Basalt			Near McCoy, Dotsero, and Aspen; ages 0.004-1.7 m.y.
Pliocene and Miocene, or Miocene	Browns Park, Troublesome, and Dry Union Fms.	~1,000	~3,000	Browns park west of Gore Range; Troublesome in Williams Fork valley; Dry Union in Arkansas and upper Blue River valleys.
	Basalt	275	900	Various ages, 8-24 m.y.
	Siliceous intrusive rocks			At Treasure Mtn. near Marble (age 12.5 m.y.) and at other scattered localities.
Oligocene	Intrusive rocks			Large bodies in Elk Mtns. and others elsewhere; ages mainly 29-35 m.y.
	Volcanic rocks			Main body is in Grizzly Peak caldera; age >34 and <42 m.y.
Eocene	Uinta Fm.	~300	~1,000	Formerly Evacuation Creek Mbr. of Green River Fm.
	Green River Fm.	975	3,200	Thins southward to depositional margin on south side of Grand Mesa.
	Intrusive rocks			Mainly in Twin Lakes stock in Sawatch Range and bodies near Breckenridge; ages 41-49 m.y.
Eocene, or Eocene and Paleocene	Wasatch Formation	1,525	5,000	In central Piceance Basin includes Fort Union equivalent at base.
Paleocene	*Middle Park Fm. (upper part)	~600	~2,000	Unconformably overlaps from Cretaceous to Precambrian rocks.
	**Ohio Creek Fm.	122	400	Thins northward.
Paleocene and Late Cretaceous	Intrusive rocks			In many bodies from Aspen northeastward; ages mainly 55-70 m.y.
Late Cretaceous	*Pierre Shale	1,605	5,300	Upper part missing; cut out by unconformities or faults.
	**Mesaverde Group or Fm.	1,860	6,100	Thins southward by intertonguing with Mancos Shale.
	*Niobrara Fm.	183	600	Thins westward and becomes tongue in lower Mancos Sh.
Late and Early Cretaceous	*Benton Shale	122	400	Frontier Ss. and Mowry Sh. equivalents at top; passes westward into lower Mancos Sh.
	**Mancos Shale	~1,830	~6,000	Thickens southward; includes lower Pierre, Niobrara, Benton, Frontier, and Mowry equivalents.
Early Cretaceous	Dakota Sandstone	~75	250	Thins eastward.
	Burro Canyon Fm.	70	225	Recognized only in Aspen-Basalt area.
Late Jurassic	Morrison Fm.	~150	500	Thins at Gore fault and eastward, where overlaps Precambrian.
Middle Jurassic	Curtis Fm.	<30	<100	Mainly in Colorado River area near McCoy; overstepped eastward by Morrison Fm.
	Entrada Sandstone	30	100	Truncated beneath Morrison near Gore fault and west of Aspen.
Early Jurassic and Late Triassic	Glen Canyon Sandstone	23	75	Also known as Navajo Sandstone; southern limit is near New Castle.
Late Triassic	Chinle Fm.	365	1,200	Thickness <150 m in most areas but 365 m in Hardscrabble Mtn. area; truncated beneath Entrada or Morrison in Elk Mtns. and Gore Range.
Early Triassic and Permian	State Bridge Fm.	~1,525	~5,000	Thickness <200 m in most areas but ~1,525 m in Hardscrabble Mtn. area; is a Moenkopi-Park City equivalent; depositional edge near Gore fault; truncated beneath Chinle or Entrada in southern Grand Hogback and Elk Mtns.
Permian and Pennsylvanian	Weber Sandstone	30	100	From northern Grand Hogback, thins to east and south by facies change into Maroon Fm. and also by truncation beneath State Bridge.
	Maroon Formation	~4,575	~15,000	Thins eastward and northward from Aspen area to depositional margin along Gore Range and east of Breckenridge; lower part intertongues with Eagle Valley Evaporite.

Continued on facing page

Table 1.-Principal rock units in west-central Colorado--continued

Age	Formation or unit	Maximum thickness Meters	Feet	Remarks
Pennsylvanian	Eagle Valley Evaporite or Fm.	Indeterminate		Basinal evaporitic and color-transitional facies; intertongues with Maroon, Minturn, Gothic (of Langenheim, 1952), and Belden Fms.
	Minturn Fm. and Gothic Fm. of Langenheim (1952)	~2,000	6,600	Coarse clastic facies that grades into and intertongues with Eagle Valley Evaporite; eastern depositional margin near Gore fault and Breckenridge.
	Belden Fm.	275	900	Thins eastward to depositional margin west of Gore fault and south of Breckenridge.
	Molas Fm.	23	75	Discontinuous along pre-Belden unconformity.
Early Mississippian	Leadville Limestone	84	275	Truncated beneath Belden near Gore Range and at Treasure Mtn.
Mississippian or Devonian	Chaffee Group: Gilman Sandstone	15	50	Low-relief erosional unconformities at top and base; truncated beneath Belden or Minturn near Gore Range and south of Breckenridge, and at Treasure Mtn.
Mississippian(?) and Devonian	Chaffee Group: Dyer Dolomite	53	175	In White River uplift, contains a lower limestone unit that is absent to east and south; truncated beneath Belden or Minturn near Gore Range and at Treasure Mtn.
Late Devonian	Chaffee Group: Parting Fm.	30	100	Thins and coarsens eastward; near Gore fault lies on Precambrian and is overstepped by Minturn.
Late Ordovician	Fremont Limestone	20	65	Preserved beneath pre-Parting unconformity only in western Elk Mts.
Middle Ordovician	Harding Sandstone	25	80	Preserved beneath pre-Fremont and pre-Parting unconformities only on northeast margin of Sawatch Range and in western Elk Mtns.
Early Ordovician	Manitou Dolomite	75	250	Truncated beneath Harding near Tennessee Pass and beneath Parting near Gore fault.
Late Cambrian	Dotsero Fm.	30	100	Present only in White River uplift.
	Peerless Fm.	45	150	Irregularly eroded beneath pre-Manitou and younger unconformities.
	Sawatch Quartzite	90	300	Do.
Precambrian Y	Granitic rocks			Age about 1,400 m.y.
Precambrian X	Granitic and mafic rocks			Age about 1,700 m.y.
	Metasedimentary and metavolcanic gneisses			Age 1,750-1,800 m.y.

an episode of uplift and erosion that was much briefer than those preceding. The erosion was responsible in some part for regional variations in thickness of the underlying Dyer Dolomite, though there were evidently also differences in depositional thickness. The Dyer has a maximum thickness of about 53 m in the White River uplift (Bass and Northrop, 1963; Campbell, 1970): it is as little as 12 m thick in the Mosquito Range near Alma (Singewald and Butler, 1941), where it is obviously unevenly eroded beneath the Gilman Sandstone, and as little as 6 m near the Mosquito fault in the Tenmile Range north of Climax (Tweto, 1949). In mine workings at Gilman and in outcrop north of Tennessee Pass, Gilman Sandstone fills gentle-sided channels cut to a depth of as much as 9 m into the Dyer.

An unconformity at the base of the Leadville Limestone (as here used and as redefined by Tweto and Lovering (1977) is subtle in most places but locally has a relief of a few meters. Some depressions in the surface of unconformity contain scattered pebbles of older Paleozoic rocks, such as quartzites from the Parting or Sawatch, and distinctive cherts from the Manitou, or even of quartz (Johnson, 1944) that presumably came from Precambrian rocks. This indicates the presence, somewhere in the region, of an uplift not covered by the Gilman Sandstone. The uplift was perhaps the same as the inferred Devonian "high" at or near the site of the Gore Range, but no direct evidence of this is known.

A major unconformity at the base of the Pennsylvanian sequence transects rocks of all ages down to the Precambrian. Where underlain by Paleozoic carbonate rocks, the unconformity is in many places an irregular karst erosion surface. This surface is chiefly on Leadville Limestone, but locally it extends down to levels as low as the Manitou Dolomite. The discontinuous and markedly irregular Molas Formation is a largely regolithic deposit on this surface, and Molas-like material fills caves and channels in underlying carbonate rocks. The Molas, however, is not entirely regolithic. Even where on top of the Leadville, it contains foreign materials as old as Precambrian, attesting to the presence of nearby uplifts at the time it accumulated. These uplifts were the late Paleozoic

Front Range and Uncompahgre highlands, discussed below. A Sawatch Range highland has also been postulated on the basis of sedimentational features in the Mississippian rocks on the flanks of the range (DeVoto and Maslyn, 1977), but as these same features occur regionally, the argument is not persuasive.

LATE PALEOZOIC DEFORMATION AND SEDIMENTATION

Two major highlands of the Ancestral Rockies, the Front Range on the northeast and the Uncompahgre on the southwest, rose in Colorado in the Early Pennsylvanian, as summarized by Mallory (1972). Parts of the two highlands and the intervening sedimentary trough occupy the area discussed in this article (Fig. 1). The highlands persisted until the Late Triassic, but they are generally designated as "late Paleozoic" for their time of origin and greatest manifestation and to distinguish them from modern features with the same names.

The late Paleozoic Front Range highland included the site of the present Gore Range as well as that of the Front Range to the east. The Gore fault formed a lengthy segment of the western border of the highland as demonstrated by stratigraphic, sedimentational, and structural features. Between the upper Eagle River and the fault, Pennsylvanian rocks overstep the Leadville, Gilman, and Dyer Formations. At or near the fault, they overstep the Parting Formation and rest on Precambrian rocks as they do also in many localities from McCoy to Breckenridge. The Pennsylvanian rocks themselves document the strong influence of the fault. In several places near the Gore fault, the Robinson Limestone Member of the Minturn Formation, which normally is about 1,340 m above the Belden Formation, is only 30 m or less stratigraphically above Precambrian rocks. Most of the missing section of the Minturn wedges out by onlap in the fault zone or within a few kilometers to the west. Location of the depositional margin of the underlying Belden Formation is not known but probably is somewhat farther west. Near the fault, conglomerates in the Minturn are very coarse, as also are conglomerates in the overlying Maroon Formation. The Maroon Formation overlaps the Minturn, but only the uppermost part of the Maroon is present east of the fault, where it lies on Precambrian rocks. The general stratigraphic relations indicate major reactivation of the Gore fault in Pennsylvanian time. This is supported in detail by relations that indicate differential movements between fault blocks in the Gore fault zone during Minturn deposition (Tweto and Lovering, 1977).

The position and character of the border of the late Paleozoic Uncompahgre highland are not known in detail. The border area is not only deeply buried beneath the Mesozoic and Cenozoic unconformities as clearly illustrated at Treasure Mountain dome near Marble (Gaskill and Godwin, 1966; Mutschler, 1970). A zone or belt in which the depositional margin of Pennsylvanian and Lower Permian rocks is inferred to have lain is indicated in Figure 1.

Uplift of the Uncompahgre and Front Range highlands evidently was accompanied by some deformation in the intervening area. Fracture systems developed in rocks as young as the Leadville Limestone, and these guided karst dissolution in at least some places. In the Aspen area, DeVoto and Maslyn (1977) have interpreted certain geologic relations as evidence of post-Leadville, pre-Belden faulting, though Bryant (1971) interpreted the relations differently.

The late Paleozoic Front Range and Uncompahgre highlands were separated by a trough in which a thick sequence of Pennsylvanian and Permian sediments accumulated. This trough and its sediments have been amply described (Mallory, 1972; Murray, 1958; Brill, 1952). In general, coarse arkosic clastic rocks of the Minturn, Gothic (of Langenheim, 1952), and Maroon Formations occupy the sides of the trough, and evaporites and related rocks of the Eagle Valley Evaporite (or Formation) occupy the center, overlain by the upper part of the Maroon Formation.

The evaporitic rocks are of special interest because of their apparent effect on later sedimentation and tectonics. They are preserved in central Colorado in a large northwestern area called the Eagle basin (Fig. 1), in South Park south of Fairplay, and in the valley of the Arkansas River and adjoining northern Sangre de Cristo Range southeast of Salida, Colo. The evaporitic rocks intertongue principally with the Minturn Formation, but they occur also at stratigraphic levels as low as the Belden Formation and as high as the lower part of the Maroon Formation. They consist of gypsum or anhydrite, associated siltstones and shales, minor carbonate rocks, and, as shown by two oil-test borings in the Eagle basin, of salt. Their character and the distribution of facies in the Eagle basin, where they constitute the Eagle Valley Evaporite, have been summarized by Mallory (1971).

The maps of the Eagle basin by Mallory (1971) depict the present distribution of evaporites; and with some local exceptions, his discussion assumes a generally similar original distribution. Regional stratigraphic and structural relations suggest otherwise. In this paper, I propose that large-scale flowage of evaporites began as early as Permian time, was the cause of great and abrupt local increases in thickness of the State Bridge, Chinle, and possibly the Maroon Formation, and was responsible for some peculiar and major "faults" in the present structure. The inferred original distribution of major Pennsylvanian evaporite deposits in west-central Colorado is shown in Figure 1.

INFLUENCE OF EVAPORITES ON SEDIMENTATION

In the area between Aspen and Eagle, the Maroon, State Bridge, and Chinle Formations are markedly thicker than elsewhere in the region, and the change from normal thicknesses is abrupt. The Maroon reaches a thickness of about 4,500 m a few kilometers north of Aspen (Freeman, 1972a; Freeman and Bryant, 1977), whereas its thickness throughout the region to the north and east is 600-1,200 m and in the Elk Mountains to the west a maximum of 2,900 m is preserved (Bryant, 1969). An unconformity between the Maroon and State Bridge accounts for some variations in thickness of the Maroon. However, the unconformity is most pronounced in the area of thickest Maroon and in most other places is subtle or even undetectable. It probably does not account for the great differences in thickness of the Maroon. The State Bridge has an estimated thickness of about 1,575 m at Hardscrabble Mountain (Plate 1) and is 730 m thick in the Fryingpan River area (Freeman, 1971a), whereas in bordering areas and regionally to the east and north its thickness is 200 m or less. Again, an unconformity between the State Bridge and the Chinle Formation accounts for some thinning of the State Bridge, particularly to the west, but an upper member (the Sloane Peak) is common both to the thick and the thin or normal sections (Freeman, 1971a), indicating that the State Bridge was neither deeply nor widely eroded. The Chinle is also abnormally thick in the Hardscrabble area, reaching 335 m, whereas in the surrounding region it is 60-120 m thick (Stewart and others, 1972). An unconformity between the Chinle and Entrada accounts for thinning of the Chinle below its regional norm, but as with the State Bridge, there is no indication that a major part of the Chinle was removed everywhere except in the Hardscrabble area.

The general area of thick Maroon Formation is designated the Maroon depocenter (Fig. 1) and the area of thickest State Bridge and Chinle is designated the State Bridge-Chinle depocenter. Owing to truncation by erosion and faulting, the boundaries of the two centers can be only approximate.

The two depocenters might reflect localized and rapid subsidence of the basement, presumably in response to sedimentary loading. If so, the abruptness of the change in thickness would remain to be explained. The State Bridge is 1,575 m thick on the west side of the Fulford stock (Plate 1) and 90 m thick on the east side. Alternatively, the depocenters might reflect large-scale flowage of evaporites. Structural evidence (discussed below) of flowage at least as early as post-Maroon, pre-State Bridge time supports this argument, as do stratigraphic relations revealed in a test boring on Red Table Mountain (Pan American No. 1 Tully, sec. 30, T. 6 S., R. 85 W.). This boring encountered no evaporite section and only 150 m of Minturn or nonevaporitic Eagle Valley rocks between the Maroon and the Belden (Am Strat log D-1819). This locality was not beyond the southern limit of evaporite deposition, for thick evaporite occurs farther south, at Ruedi Reservoir (Plate 1).

If flowage of evaporites beneath the Maroon depocenter occurred during Maroon deposition, it would have drawn to a close as the supply of evaporites dwindled, leaving the site ineligible — from this cause — for abnormally thick accumulation of younger sediments. This fits the observed facts. The Maroon thins northward rapidly as the State Bridge thickens, and as the two are separated by an unconformity that is locally angular (Freeman, 1971a, b) the relations cannot be ascribed to intertonguing or facies change.

The area of the State Bridge-Chinle depocenter is now dissected and partly encircled by diapiric bodies of evaporites. The thickness of the evaporites before flowage is unknown but probably was at least some hundreds of meters. A test boring started in gypsum at Eagle (Mallory, 1971) passed through 1,732 m of evaporite-bearing rocks and entered intrusive igneous rock at a depth of 1,860 m. A boring south of Glenwood Springs, in the diapiric Cattle Creek anticline (Plate 1), was in evaporites to total depth of 933 m, the last 275 m being mainly in salt (Mallory, 1966).

INFLUENCE OF EVAPORITES ON STRUCTURE

Structural features of various kinds and magnitudes and of Permian, post-Createaceous, and essentially modern ages evidently resulted from flowage of evaporites. A major Permian syncline probably was at the site of Red Table Mountain, which now is a broad west-northwest-trending anticline in the Maroon Formation. As noted by Freeman (1971-b), the absence of evaporites and the near-absence of equivalent rocks in the Tully test well suggests that the Red Table Mountain area was the site of a Permian syncline from which evaporites were squeezed into adjoining anticlines. Evidence of an evaporite-bearing anticline to the south is seen both in modern structure and in Maroon-State Bridge stratigraphic relations in the Fryingpan River area as illustrated by a map by Freeman (1972a). The anticline to the north of the Permian syncline is a gypsum diapir between Red Table and Hardscrabble Mountains (Plate 1). Freeman (1971-b) noted that in this structure, the State Bridge is unconformable on the Maroon and locally on the Eagle Valley Evaporite. A pre-State Bridge anticline in the Maroon Formation on the northeast side of the Roaring Fork valley between Aspen and Basalt was also described by Freeman (1971-b), who inferred that it might be related to a basement fault. As the Castle Creek fault (Plate 1) more or less parallels the fold, this may be true, but considering that the fault brings up slices of evaporites, evaporite flowage may also have been a factor in development of the anticline in Permian time. The Cattle Creek diapiric anticline, south of Glenwood Springs, was

described by Mallory (1966), who recognized that flowage may have started as early as Permian time but also noted evidence of Quaternary movement.

Post-Createaceous flowage or diapirism is the evident cause of some major structural features in the area between the Sawatch Range and the White River uplift. This surge of diapirism probably began during Laramide orogeny but continued — episodically, at least — into the Quaternary. The intrusive contacts of the evaporite diapirs have the effect of faults, and they seem to have been modified in places by fault movements. They are distinguished by a special symbol on Plate 1.

Hardscrabble Mountain is a conspicuous example of the effects of diapirism. The mountain consists of formations from the Maroon into the Mancos Shale in a north-dipping homoclinal slab almost entirely surrounded by gypsum. The contact of the clastic rocks of the mountain with the gypsum is interpreted to be intrusive, possibly modified by fault movements, and forms an almost-closed elliptical "diapiric contact-fault" (Plate 1). A complementary structure to the north of the ellipse lies north of Eagle, and the complementary structure to the south extends along the lower slopes of Red Table Mountain where, again, red beds of the Maroon Formation dip into diapiric gypsum.

An example of late Tertiary or Quaternary diapirism is an anticline longitudinally bisected by the Eagle River between Gypsum and Dotsero, described by Benson and Bass (1955). Basalt on the north flank of the anticline, dated as 22 m.y. in age (Larson and others, 1975), has been let down to its present position by faults and, quite possibly, by dissolution of evaporites. The basalt dips north in accordance with its position on the anticline. Thus the anticline is younger than 22 m.y., and geomorphic relations suggest that it is much younger. The anticline is in an area of subsided Maroon Formation and in effect forms a narrow belt of evaporites bisecting what was once a single plate of the Maroon in a sea of gypsum. The subsidence of the Maroon plate could have been complementary to diapiric uplift elsewhere, but large-scale dissolution of evaporites also could have been a factor.

EARLY MESOZOIC UNCONFORMITIES AND TECTONIC MOVEMENTS

An unconformity at the base of the Chinle Formation, mentioned previously, truncates the State Bridge Formation in the southern Grand Hogback and eastern Elk Mountains, indicating renewed uplift of the Uncompahgre highland in — presumably — Middle Triassic time. Movement on generally north-trending faults in the eastern Elk Mountains occurred at the same time, as shown by changes in thickness or even the termination of the State Bridge at faults (Freeman and Bryant, 1977; Bryant and Freeman, 1977; Bryant, 1972). From the Aspen area southward to the Gunnison River and beyond, record of these events is obliterated by an unconformity at the base of the Entrada Sandstone. This unconformity records not only Early Jurassic regional uplift but differential uplift of both the Uncompahgre and the Front Range highlands. A fine example of the effect near the Uncompahgre highland border is at Treasure Mountain dome, where the Entrada oversteps from the Maroon Formation down to the Peerless Formation (Gaskill and Godwin, 1966; Mutschler, 1970). Renewed movements also occurred on some of the faults that had moved in Middle Triassic time. In places near the Gore fault, at the border of the Front Range highland, the unconformity truncates the Chinle, and the Entrada lies on the Maroon Formation, indicating pre-Entrada movement on the fault. Except in the sedimentary-rock embayment that comes to a point at Dillon (Fig. 1), the Entrada is absent between the Chinle and Morrison Formations east of the Gore fault in the area shown in Plate 1. Immediately to the north, however, a thin wedge of the equivalent Canyon Springs Member of the Sundance Formation lies between the Morrison Formation and Precambrian rocks on the east flank of the Gore Range (Pipiringos and others, 1969).

A pre-Morrison unconformity records further movements on the Gore fault and the faults in the Elk Mountains mentioned above. Between these faults, the Curtis Formation probably was widely removed. In places near the Gore fault, the Morrison Formation rests successively eastward on the Entrada, Chinle, and Maroon Formations, and a short distance east of the fault zone it lies on Precambrian rocks (Tweto and others, 1970). In the same area, Morrison thicknesses reflect fault movements. West of the fault the Morrison is about 315 m thick, and the lower half is mainly sandstone; east of the fault is only half as thick, and the lower sandstone section is greatly abbreviated. In the Elk Mountains, the Morrison lies on thin Entrada on the east side of a north-trending fault near Snowmass-at-Aspen and on the Maroon Formation on the west side (Bryant, 1972; Bryant and Freeman, 1977). To the southwest, however, at Treasure Mountain and in the direction of the Uncompahgre highland, the Entrada reappears beneath the Morrison. This suggests that the Elk Mountains area underwent some uplift independent of the main Uncompahgre uplift in the Middle Jurassic.

An unconformity at the base of the Dakota Sandstone accounts for some variations in thickness of the Morrison Formation but records no major tectonic movements in the area under discussion. Both the Morrison and Dakota thin eastward toward the present Front Range, indicating that the old Front Range highland was slightly positive into Dakota time.

LARAMIDE OROGENY

The history of Laramide orogeny in the Southern Rocky Mountains has been discussed elsewhere in some detail (Tweto, 1975). In brief, orogeny began in west-central Colorado with uplift of the Sawatch Range. This range is a huge anticline, but abundant Cretaceous and Tertiary instrusive rocks through its length suggest that it may be more an elongate intrusive dome than a compressional anticline. The range rose rapidly. As dated by ammonite zones calibrated with radiometric time, the uppermost part of the Mancos Shale and basal part of the Mesaverde Formation were being deposited in the Aspen area 71-72 m.y. ago. By 69-70 m.y. ago, fault-controlled porphyries were being emplaced into the sedimentary rocks on the flanks of the anticline in the Aspen and Leadville areas. The range was rapidly eroded, and Paleozoic rocks on it supplied fossiliferous cherts to the Paleocene Ohio Creek Formation, which is interpreted as a lag concentrate between the Sawatch Range and basins of Fort Union deposition to the north. Volcanic and igneous intrusive activity occurred while erosion of the range was in progress. Abundant volcanic debris was contributed to the Wasatch Formation in the southern part of the Piceance basin, and some found its way as far north as the Sand Wash basin in far northwest Colorado.

The Gore and Front Ranges rose at the site of the ancient Front Range highland slightly later than the Sawatch Range, probably near the end of the Cretaceous. In the northeast corner of the area covered in Plate 1, Paleocene rocks of the Middle Park Formation lie on Precambrian rocks, and farther northeast, on deformed sedimentary rocks ranging from Morrison to Pierre. The early Laramide tectonic spasm indicated by these relations also produced the Williams Range thrust fault, which predates the Middle Park Formation (Izett, 1975).

The Mosquito Range, which is a portion of the east flank of the Sawatch anticline, certainly began to rise differentially at the time the Gore and Front Ranges rose, but the modern range is largely a product of a later event, discussed later. The Elk Mountains are a structural bench on the west flank of the Sawatch anticline, and they could have had their first expression as early as the Sawatch Range. Bryant (1966) has interpreted the Elk Range thrust fault (Plate 1) as a gravity slide off the Sawatch Range. Assuming this to be so, the Elk Mountains might somewhat postdate the Sawatch structure.

The last of the major Laramide uplifts and strutural features to form were the White River uplift and Grand Hogback, evidently in the late Eocene. The White River uplift is a broad structural dome, and the Grand Hogback is a long, sinuous, steep monocline that flanks the western and part of the southern sides of the dome and then extends southward into the Elk Mountains (Plate 1). Both structures postdate the lower and middle Eocene Wasatch and Green River Formations. These formations show little or no evidence of an eastern depositional limit at the present limit of preservation along the Grand Hogback. Both formations are upturned in the Grand Hogback structure along the west side of the White River uplift. Some part of the upturning probably resulted from late Tertiary re-elevation of the White River dome, but geologic relations to the south establish the Grand Hogback monocline to be primarily a Laramide structure. Near the Crystal River, the monocline flattens, becomes broader, and is disrupted by subsidiary faults and folds that are cut by undeformed Oligocene intrusive bodies (Obradovich and others, 1969).

TERTIARY IGNEOUS EVENTS

Igneous activity in the region began in latest Cretaceous time, continued episodically through the Tertiary, and, on a minor scale, extended into the Quaternary. Three main episodes are recognized. The first, of Laramide age, is represented now only by intrusive rocks, but the evidence from the Laramide sedimentary sequence (Wasatch Formation) indicates that andesitic volcanism accompanied the intrusive activity. The second episode occurred in the Oligocene and is represented in west-central Colorado by numerous intrusive bodies and subordinate volcanic rocks. The third episode was largely in the Miocene and is represented by extensive basalts and subordinate granitic or rhyolitic intrusive rocks.

The Laramide intrusive bodies are largely in the Colorado mineral belt (Tweto and Sims, 1963), which extends northeastward across the southeastern corner of the area shown in Plate 1 in a belt bounded approximately by Dillon, Gilman, and Aspen on the northwest and by Fairplay and Granite on the southeast. However, other Laramide intrusive bodies lie in a northwest-trending line in the northern Sawatch Range, almost normal to the mineral belt (Plate 1). This line ends in surface exposures with the Fulford stock, but the intrusive rock encountered in the test well at Eagle, mentioned previously, suggests that it continues northwestward toward the east side of the White River uplift. The northwest-trending line of intrusives is paralleled by scattered but fairly persistent faults, some of which contain porphyry dikes (Tweto, 1974), and it evidently reflects a major flaw in the deep basement.

Oligocene intrusive bodies are most abundant in the Elk Mountains but occur also in the central and southern Sawatch Range, the Climax area, and in an isolated stock north of McCoy (Plate 1). Oligocene volcanic rocks are preserved only locally in the area but probably once were widespread (Steven, 1975). The largest body is in the Grizzly Peak caldera and immediate vicinity. Ashflow tuffs from this caldera have not been recognized elsewhere, but they probably blanketed an extensive area in the Sawatch Range in the Oligocene. A small

body of ashflow tuff west of Basalt is somewhat younger than the volcanics of the caldera; its source is unknown but probably was in the Elk Mountains. Volcanic rocks in the extreme southeast corner of the area of Plate 1 are an outlier of an extensive volcanic field farther southeast in South Park. Except for a concentration of intrusives in the general vicinity of the mineral belt, the Oligocene igneous features show no evident control by master structural features comparable to the Homestake and related shear zones that seem to have controlled the Laramide igneous episode.

Basalts are widely distributed in the region (Plate 1), and they probably blanketed much larger areas in the Miocene. They are mostly in the age range 8-24 m.y., but Pleistocene basalts are present in small bodies near Aspen and McCoy, and Holocene basalt in a small body at Dotsero (Larson and others, 1975). The older basalts are in part interbedded with the Browns Park Formation in the Flat Tops and Piney River basalt fields (Plate 1). The chief body of silicic rock of the regional basalt-rhyolite association is at Treasure Mountain, though small bodies are scattered elsewhere. The body at Treasure Mountain is a sodic granite dated as about 12.5 m.y. in age (Obradovich and others, 1969). Intrusion of the granite created the structural dome at the site, and thanks to later erosion, the dome reveals important stratigraphic relations on the flank of the otherwise buried late Paleozoic Uncompahgre highland. The basalt-rhyolite igneous episode is related in general in Colorado to crustal extension as exemplified principally by the Rio Grande rift system and associated block faulting (Lipman and Mehnert, 1975). The rift system, discussed below, is prominent in the eastern part of the area, but faults of the system have not been recognized in the western part despite the occurrence there of extensive basalt fields and the Treasure Mountain dome. The magmas probably rose along basement fracture systems with trends other than that of the rift system. Dikes that were evident feeders for the basalts of the Grand Mesa area trend east-west, and feeder dikes and plugs in the Flat Tops basalt field are crudely alined west-northwest (Tweto and others, 1976).

LATE TERTIARY DEFORMATION AND SEDIMENTATION

Late Tertiary rifting and block faulting were extensive in the eastern part of the area. They were accompanied there and elsewhere both by differential re-elevation of mountain units and by general uplift of the entire region. The rifting and block faulting were closely related in time to the basaltic volcanism discussed above, and they were accompanied by sedimentation in the areas between uplifts. The fault movements created the grabens of the Arkansas valley and Williams Fork (Plate 1), in which accumulated, respectively, the Dry Union and Troublesome Formations. In the structural sag between the Gore Range and the White River uplift and northward, the Browns Park Formation was deposited.

The late Tertiary faulting in this region is a northern expression of the Rio Grande rift. This major intracratonic fracture zone extends from the Rio Grande Valley in New Mexico northward through the San Luis Valley of southern Colorado and through the length of the valley of the upper Arkansas River. As a continuous graben, the rift ends near Leadville, but rift-related movements on old faults occurred from the Leadville area far northward. The Arkansas Valley graben, only the northern end of which is encompassed on Plate 1, slices through the eastern flank of the giant Sawatch Range anticline. The Mosquito Range, east of the graben, is a part of the anticline, capped by east-dipping sedimentary rocks. The Mosquito fault (Plate 1) is the master fault along the west side of the Mosquito Range and its northern extension, the Tenmile Range. The Mosquito fault was a major fault in Laramide time and was very extensively reactivated in the late Tertiary. A post-Oligocene displacement of as much as 2,750 m at Climax has been postulated (Wallace and others, 1968). In the Leadville area, faults subsidiary to the Mosquito displace not only the Dry Union Formation but, in decreasing amounts, a succession of glacial deposits.

The Gore Range was re-elevated as a fault block between the Gore and Blue River faults in the late Tertiary, and movements continued into the Quaternary. Remnants of the Dry Union Formation are in fault contact with Precambrian rocks along the Blue River fault (Plate 1), and in places along the fault, very recent Holocene movements occurred (Tweto and others, 1970). Similarly, the Gore fault brings the Browns Park Formation against Precambrian rocks near the Colorado River, and in places farther south, geomorphic features suggest Quaternary movements along the fault.

The Williams Fork graben is bounded on the northeast by a reactivated Precambrian fault and on the southwest side by a reactivated Laramide fault. The graben is partly filled by the Troublesome Formation, which extends into it from Middle Park, immediately to the north. Within the graben, Pleistocene gravels are displaced by faults parallel and transverse to the graben faults. To the northwest, near Kremmling, post-Troublesome movements occurred on normal faults superposed over the subcrop of the Laramide Williams Range thrust fault (Izett, 1975).

In the area west of the Gore fault, deformation by folding complemented the block faulting to the east. Lower Miocene basalt flows and overlying sediments of the Browns Park Formation in the Piney River basalt field are synclinally folded about a northwest-trending axis on the northeast flank of the

Laramide Burns-Red and White syncline (Plate 1). As noted by Hunt (1969) and by Larson, Ozima, and Bradley (1975), these same rocks are at an altitude 600-900 m higher in the Flat Tops basalt field, signifying a major post-Miocene rise of the White River uplift.

DISCUSSION

Each of the numerous tectonic events recorded in the geology of west-central Colorado was a response to a particular cause, at a particular time, operating over a region far wider than that considered in this article. Yet, a thread of continuity unites many of the events. This thread was supplied in part by structures such as the Gore fault that participated repeatedly in tectonic events that were otherwise separate and distinct. Presumably, at the time of any given event, those preexisting structures that were so oriented that they might fulfill some of the needs in crustal yielding were reactivated. Those that were not suitably oriented reached the end of their participatory lives. They are buried inconspicuously in the rock record where, figuratively speaking, they are overwhelmed by the tectonic noise of later deformations. They will be identified — as many more are certain to be — only by careful studies in **all** kinds of geologic terranes.

A second element in the thread of continuity is the repetition in style through many tectonic events. Repeatedly through Phanerozoic time, highlands or mountain ranges rose by dip-slip movements on steep faults. Except for subsidiary fracturing, little other deformation occurred in connection with the uplifts that preceded Laramide orogeny. Viewed broadly, the chief structures of even the Laramide are monoclinal, over known or probable faults. Though not to be pursued here, the cause of the repetition in style may lie in a compositional peculiarity of the lithosphere in this part of the Phanerozoic craton, producing a prolonged tendency for parts of the crust in Colorado to "float". Alternatively, and as often suggested, the style may reflect a special cratonic type of yielding to plate-tectonic events at the distant western margin of the continent. If so, repeated plate-tectonic events through all of Phanerozoic and probably some of Precambrian time are implied.

REFERENCES CITED

Barclay, C. S. V., 1968, Geology of the Gore Canyon area, Grand County, Colorado: U.S. Geol. Survey Open-file rept., 187 p.

Bass, N. W., and Northrop, S. A., 1963, Geology of Glenwood Springs quadrangle and vicinity, northwestern Colorado: U.S. Geol. Survey Bull. 1142-J, 74 p.

Behrendt, J. C., and Bajwa, L. Y., 1972, Bouguer gravity map of Colorado: U.S. Geol. Survey Geophys. Inv. Map GP-895.

Benson, J. C., and Bass, N. W., 1955, Eagle River anticline, Eagle County, Colorado: Am. Assoc. Petroleum Geologists Bull., v. 39, no. 1, p. 103-106.

Brill, K. G., Jr., 1952, Stratigraphy in the Permo-Pennsylvanian zeugogeosyncline of Colorado and northern New Mexico: Geol. Soc. America Bull., v. 63, no. 8, p. 809-880.

Bryant, Bruce, 1966, Possible window in the Elk Range thrust sheet near Aspen, Colorado, *in* Geological Survey Research, 1966: U.S. Geol. Survey Prof. Paper 550-D, p. D1-D8.

________1969, Geologic map of the Maroon Bells quadrangle, Pitkin and Gunnison Counties, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-788.

________1971, Geologic map of the Aspen quadrangle, Pitkin County, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-933.

________1972, Geologic map of the Highland Peak quadrangle, Pitkin County, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-932.

Bryant, Bruce, and Freeman, V. L., 1977, Geologic summary of the Aspen area, Southern Rocky Mountains, Colorado (this volume).

Campbell, J. A., 1967, Dispersal patterns in Upper Devonian quartzose sandstones in west-central Colorado, *in* Oswald, D. H., ed., International symposium on the Devonian System, Calgary, Alberta, Sept. 1967: Calgary, Alberta Soc. Petroleum Geologists, v. 2, p. 1131-1138.

________1970, Stratigraphy of Chaffee Group (Upper Devonian) west-central Colo.: Am. Assoc. Petroleum Geologists Bull., v. 54, no. 2, p. 313-325.

DeVoto, R. H., and Maslyn, R. M., 1977, Sedimentology and diagenesis of the Leadville Formation and controls of lead-zinc-silver deposits, central Colorado (abs.): Mtn. Geologist, v. 14, no. 1, p. 27-28.

Freeman, V. L., 1971a, Stratigraphy of the State Bridge Formation in the Woody Creek quadrangle, Pitkin and Eagle Counties, Colorado: U.S. Geol. Survey Bull. 1324-F, 17 p.

________1971b, Permian deformation in the Eagle basin, Colorado, *in* Geological Survey Research, 1971: U.S. Geol. Survey Prof. Paper 750-D, p. D80-D83.

________1972a, Geologic map of the Ruedi quadrangle, Pitkin and Eagle Counties, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-1004.

________1972b, Geologic map of the Woody Creek quadrangle, Pitkin and Eagle Counties, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-967.

Freeman, V. L., and Bryant, Bruce, 1977, Red bed formations in the Aspen region: (this volume).

Gaskill, D. L., and Godwin, L. H., 1966, Geologic map of the Marble quadrangle, Gunnison and Pitkin Counties, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-512.

Hansen, W. R., 1971, Geologic map of the Black Canyon of the Gunnison River and vicinity, western Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-584.

Hunt, C. B., 1969, Geologic history of the Colorado River, *in* The Colorado River region and John Wesley Powell: U.S. Geol. Survey Prof. Paper 669-C, p. 59-130.

Isaacson, L. B. and Smithson, S. B., 1976, Gravity anomalies and granite emplacement in west-central Colorado: Geol. Soc. America Bull., v. 87, no. 1, p. 22-28.

Izett, G. A., 1975, Late Cenozoic sedimentation and deformation in northern Colorado and adjoining areas, *in* Curtis, B. F., ed., Cenozoic history of the Southern Rocky Mountains: Geol. Soc. America Mem. 144, p. 179-209.

Johnson, J. H., 1944, Paleozoic stratigraphy of the Sawatch Range, Colo.: Geol. Soc. America Bull., v. 55, no. 3, p. 303-378.

Langenheim, R. L., 1952, Pennsylvanian and Permian stratigraphy in Crested Butte quadrangle, Gunnison County, Colo.: Am. Assoc. Petroleum Geologists Bull., v. 36, no. 4, p. 543-574.

Larson, E. E., Ozima, Minoru, 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: Geol. Soc. America Mem. 144, p. 155-178.

Lipman, P. W., and Mehnert, H. H., 1975, Late Cenozoic basaltic volcanism and development of the Rio Grande depression in the Southern Rocky Mountains, *in* Curtis, B. F., ed., Cenozoic history of the Southern Rocky Mountains: Geol. Soc. America Mem. 144, p. 119-154.

Lovering, T. S., and Johnson, J. H., 1933, Meaning of unconformities in stratigraphy of central Colorado: Am. Assoc. Petroleum Geologists Bull., v. 17, no. 4, p. 353-374.

Mallory, W. W., 1966, Cattle Creek anticline, a salt diapir near Glenwood Springs, Colorado, *in* Geological Survey Research, 1966: U.S. Geol. Survey Prof. Paper 550-B, p. B12-B15.

________1971, Eagle Valley Evaporite, northwest Colorado — a regional synthesis: U.S. Geol. Survey Bull. 1311-E, 37 p.

________1972, Regional synthesis of the Pennsylvanian System, *in* Geologic Atlas of the Rocky Mountain region: Denver, Colo. Rocky Mtn. Assn. Geologists, p. 111-142.

Murray, H. F., 1958, Pennsylvanian stratigraphy of the Maroon Trough, *in* Curtis, B. F., ed., Symposium on Pennsylvanian rocks of Colorado and adjacent areas: Rocky Mtn. Assoc. Geologists, Denver, p. 47-58.

Mutschler, F. E., 1970, Geologic map of the Snowmass Mountain quadrangle, Pitkin and Gunnison Counties, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-853.

Obradovich, J. D., Mutschler, F. E., and Bryant, Bruce, 1969, Potassium-argon ages bearing on the igneous and tectonic history of the Elk Mountains and vicinity, Colorado: A preliminary report: Geol. Soc. America Bull., v. 80, no. 9, p. 1749-1756.

Olson, J. C., Marvin, R. F., Parker, R. L., and Mehnert, H. H., 1977, Ages and tectonic setting of lower Paleozoic alkalic and mafic rocks, carbonatites, and thorium veins in south-central Colorado: U.S. Geol. Survey Jour. Research, v. 5 (in press).

Parker, R. L., and Sharp, W. N., 1970, Mafic-ultramafic igneous rocks and associated carbonatites of the Gem Park complex, Custer and Fremont Counties, Colorado: U.S. Geol. Survey Prof. Paper 649, 24 p.

Pipiringos, G. N., Hail, W. J., Jr., and Izett, G. A., 1969, The Chinle (Upper Triassic) and Sundance (Upper Jurassic) Formations in north-central Colorado: U.S. Geol. Survey Bull. 1274-N, 35 p.

Ross, R. J., Jr., 1976, Ordovician sedimentation in the Western United States, *in* Bassett, M. G., ed., The Ordovician System: proceedings of a Paleontological Association symposium, Birmingham, Sept. 1974, Univ. of Wales Press and Nat. Mus. of Wales, Cardiff, p. 73-105.

Singewald, Q. D., 1931, Depositional features of the "Parting" quartzite near Alma, Colo.: Am. Jour. Sci., 5th ser., v. 22, p. 404-413.

Singewald, Q. D., and Butler, B. S., 1941, Ore deposits in the vicinity of the London fault of Colorado: U.S. Geol. Survey Bull. 911, 74 p.

Steven, T. A., 1975, Middle Tertiary volcanic field in the Southern Rocky Mountains, *in* Curtis, B. F., Cenozoic history of the Southern Rocky Mountains: Geol. Soc. America Mem. 144, p. 75-94.

Stewart, J. H., Poole, F. G., and Wilson, R. F., 1972, Stratigraphy and origin of the Chinle and related Upper Triassic strata in the Colorado Plateau region: U.S. Geol. Survey Prof. Paper 690, 336 p.

Tweto, Ogden, 1949, Stratigraphy of the Pando area, Eagle County, Colorado: Colorado Sci. Soc. Proc., v. 15, no. 4, p. 147-235.

________1974, Geologic map and sections of the Holy Cross quadrangle, Eagle, Lake, Pitkin, and Summit Counties, Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-830.

________1975, Laramide (Late Cretaceous-early Tertiary) orogeny in the Southern Rocky Mountains, *in* Curtis, B. F., ed., Cenozoic history of the Southern Rocky Mountains: Geol. Soc. America Mem. 144, p. 1-44.

________, Bryant, Bruce, and Williams, F. E., 1970, Mineral resources of the Gore Range Primitive Area and vicinity, Summit and Eagle Counties, Colorado: U.S. Geol. Survey Bull. 1319-C, 127 p.

________, and Case, J. E., 1972, Gravity and magnetic features as related to geology in the Leadville 30-minute quadrangle, Colorado: U.S. Geol. Survey Prof. Paper 726-C, 31 p.

________, and Lovering, T. S., 1977, Geology of the Minturn 15-minute quadrangle, Eagle and Summit Counties, Colorado: U.S. Geol. Survey Prof. Paper 956 (in press).

________, Moench, R. H., and Reed, J. C., Jr., 1976, Preliminary geologic map of the Leadville 1° x 2° quadrangle, northwestern Colorado: U. S. Geol. Survey Misc. Field Studies Map MF-760.

________, and Sims, P. K., 1963, Precambrian ancestry of the Colorado mineral belt: Geol. Soc. America Bull., v. 74, no. 8, p. 991-1014.

Wallace, S. R., Muncaster, N. K., Jonson, D. C., Mackenzie, W. B., Bookstrom, A. A., and Surface, V. E., 1968, Multiple intrusion and mineralization at Climax, Colorado, *in* Ridge, J. D., ed., Ore deposits of the United States, 1933-1967 (Graton-Sales volume), vol. 1: New York, Am. Inst. Mining, Metall., and Petroleum Engineers, p. 605-640.