

Ray L. Chilcote. GEOLOGY OF THE DEADMAN GULCH DRAPE FOLD AND THE SURROUNDING AREA, UPPER SPRING CREEK CANYON, GUNNISON COUNTY, COLORADO. (Under the direction of Dr. Richard Mauger) Department of Geology, November 1996.

The Deadman Gulch drape fold, located on the western slope of the Sawatch Range, central Colorado, is a Laramide (Late Cretaceous to Early Tertiary) monoclinial flexure involving Proterozoic basement and Paleozoic strata. Burial depths of 5-7 kms allowed the Lower Paleozoic strata to act ductily. The study area is on the northeastern edge of a major fault block.

The basement thrust fault (forcing member) is not exposed. The drape fold is well exposed along Spring Creek canyon. The southeast end of the drape fold is hidden beneath Lower Paleozoic strata. An oblique/tear fault is located on the northwest end of the drape fold. Offset of the tear fault cannot be measured due to limitations of Paleozoic outcrops. However, Pennsylvanian strata lie against Cambrian strata, establishing a minimum offset.

Deep hydrothermal waters moving along basement faults dissolved the Leadville Limestone, Chaffee Limestone and Ordovician units locally. A jasperoid unit was deposited along these fault conduits (and laterally) as a void filling deposit and replacement mineral.

**GEOLOGY OF THE DEADMAN GULCH DRAPE FOLD AND THE
SURROUNDING AREA, UPPER SPRING CREEK CANYON, GUNNISON
COUNTY, COLORADO**

**A Thesis
Presented to
the Faculty of the Department of Geology
East Carolina University**

**In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Geology**

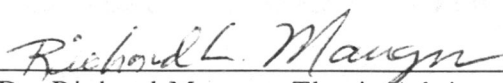
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Ray L. Chilcote**

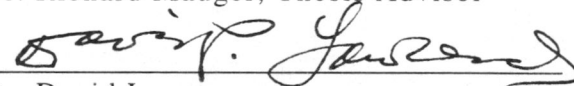
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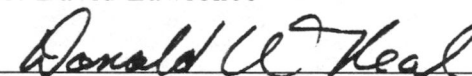
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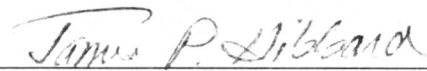
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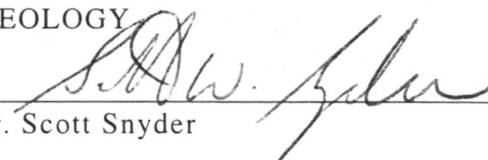

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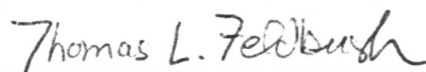

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**Mother Nature: although four snows, several hail storms, and frozen
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INTRODUCTION

Regional geologic mapping and stratigraphy in central Colorado has been published for nearly a century. However, few detailed geologic maps have been published. The Deadman Gulch drape fold has been otherwise ignored to date. Such neglect is quite surprising because one must drive through the center of the fold (perpendicular to strike) to gain access to the area to the northwest.

Structures created in ductile sedimentary strata by brittle basement block faulting are interpreted as drape (or forced) folds (Sterns, 1971, 1978; Matthews, 1978; Weinberg, 1978). Laramide drape folds are found throughout the Rocky Mountain foreland and in the central Rocky Mountains (Sterns, 1970; Cook, 1978; Couples and Sterns, 1978; Davis, 1978; Lisenbee, 1978; Matthews, 1978; Matthews and Work, 1978; McClurg, 1978; Palmquist, 1978; Sacrison, 1978; Sterns, 1978; Sterns and Sterns, 1978).

Horizontal compression (crustal shortening) and the resulting offset of basement blocks can deform overlying strata (Chamberlin, 1919, 1923; Brown, 1982; Cook, 1978; Logan and others, 1978). Such compressional forces acting on the Rocky Mountain region during the Late Cretaceous to Early Tertiary (Johnson, 1944; Lovering, 1966; Lovering, 1972; Blackstone, 1981; Hamilton, 1988) generated the Laramide orogeny. The Sawatch Range was created by the Laramide orogeny during the Late Cretaceous to Early Tertiary (Johnson, 1944).

Generally, overlying strata in drape folds develop with small, rotated, rigid blocks with minor faulting. On rare occasions, such as the

Deadman Gulch drape fold, the strata develop as a continuous, ductile fold over the brittle basement blocks without faulting. This ductile reaction by the overlying strata is caused by compressional force coupled with overburden pressure.

A jasperoid (secondary microcrystalline quartz) has locally replaced and takes the stratigraphic position of Lower Paleozoic carbonates. The jasperoid, believed to be related to fault regions and hydrothermal activity, is isolated to one formation within the drape fold. In other areas, the jasperoid replaces either portions of or the entire Lower Paleozoic carbonate sequence.

OBJECTIVES

The purpose of this study is to develop a detailed geologic map (Fig. 1) of the drape fold near the junction of Deadman Gulch and Spring Creek and to extend the mapping into adjacent areas along the northeast boundary of a large uplifted fault block. Detailed geologic mapping of the study area has not been published. Emmons (1894) published a geologic map of the Cement Mountain quadrangle. However, the east boundary of the map is located at the Deadman and Rosebud gulches junction and does not include the Deadman Gulch drape fold. Due to its small size, the drape fold is neither shown on regional geologic maps (Tweto, 1976) nor mentioned in stratigraphic studies conducted in the area (Johnson, 1944; Bush and Bush, 1972). Documentation of the drape fold and basement fault will help interpret drape folds and the orientation of regional fault trends. Cross sections will be made to understand subsurface geology. A geologic history will be developed for the study area and the drape fold.

A jasperoid (secondary microcrystalline quartz) has been deposited in a large portion of the study area. The distribution, relative geologic age, mineralogy and origin of the jasperoid will be studied to determine if it is related to the development of the drape fold. Documentation of the Deadman Gulch jasperoid will help outline regional jasperoid distribution.

LOCATION AND GENERAL DESCRIPTION

The study area is 36 kilometers northeast of Gunnison, Colorado, and includes parts of the Cement Mountain and Matchless Mountain 7½ minute quadrangles (sections 9, 13-17, and 20-29 of T14S, R84W; 38° 49' 18" N, 106° 45' 14" W). The area is located along the western flank of the Sawatch Range. The study area extends from Spring Creek valley to the divide between Cement Creek and Deadman Gulch, and covers approximately 26 square kilometers (10 square miles). Elevation ranges from 2900 to 3500 meters (9500 to 11,500 feet), resulting in 600 meters (2000 feet) of relief.

To reach the study area from Gunnison, take State Highway 135 north to Almont. Follow Forest Route 742 to Taylor Canyon (9 kms) and turn left on Forest Route 744 (Fig. 2). This road is contiguous with Spring Creek. Within one kilometer, the flood plain quickly narrows into Spring Creek Canyon. Thirteen kilometers farther up Spring Creek Canyon, Forest Service Road 744.2I intersects Spring Creek Road at the mouth of Deadman Gulch (Fig. 1). This junction is in the southeast quarter of the study area. One and one-half kilometers up Forest Service Road 744.2I, Deadman Gulch meets Rosebud Gulch. Trail 420 continues up Deadman Gulch, crosses the divide between Spring Creek and Cement Creek, and descends to Cement Creek canyon. The divide is located at the northwestern corner of the study area.

Snow drifts and avalanches may close roads above 2500 meters (8000 feet; includes the field area) until late June. However, roads are normally open by mid-June.

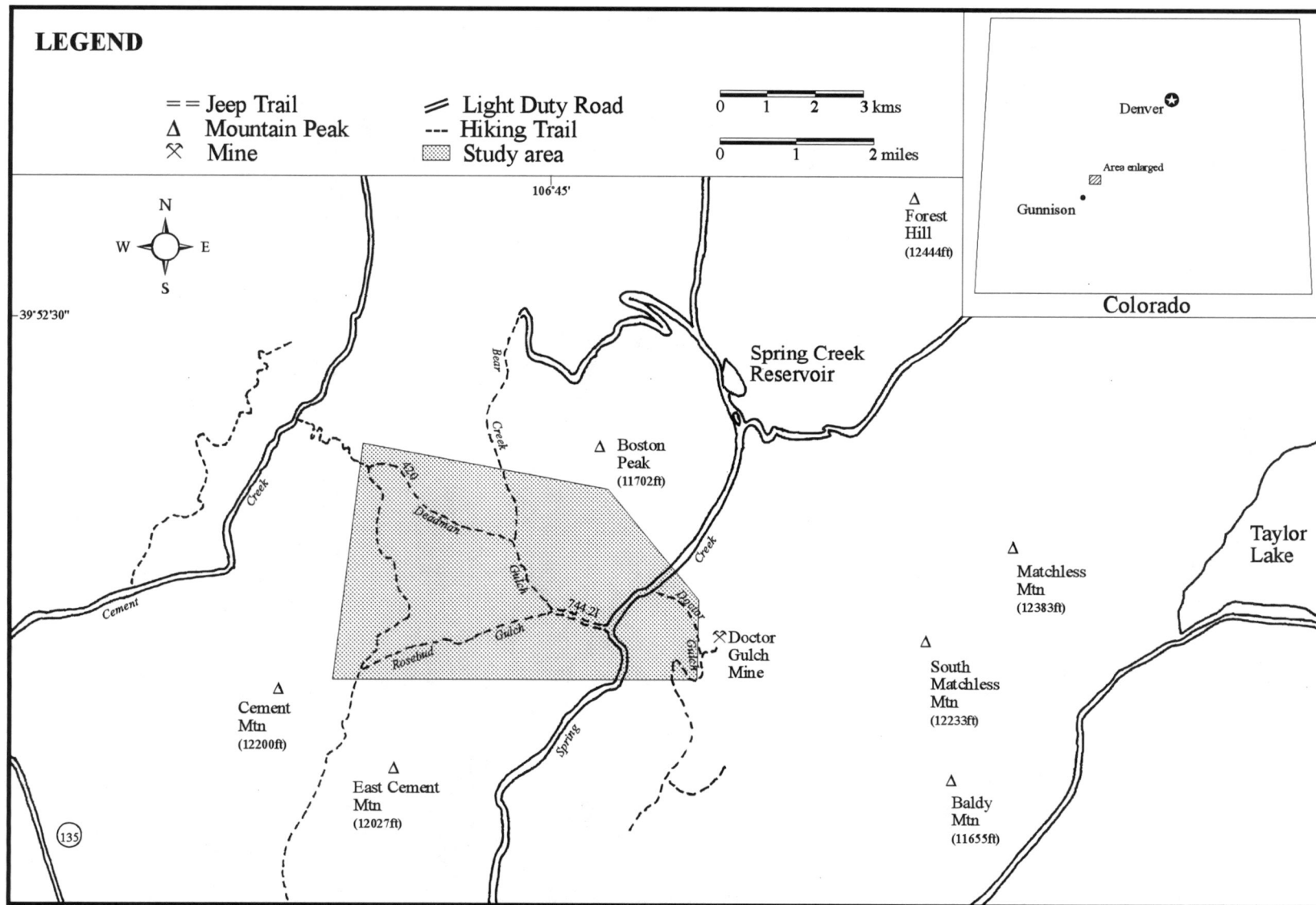


Figure 2: Location of study area

Lower Deadman Gulch is bound by steep cliffs to the northeast and steep, large boulder talus slopes to the west. The steep-sided, lower canyon gives way to a broad, open valley at the junction of Deadman and Rosebud Gulches. Numerous beaver ponds dot the small brooks and streams of the Deadman Gulch drainage.

Cement Mountain, surrounded by broadened glacial cirques, is situated at the head of the Rosebud Gulch drainage (Fig. 2). Most of the study area (and most of the region) can be seen from the summit of nearby Hill 11499 (Fig. 3).

Grassy meadows characterize areas underlain by the Belden Shale. Engleman Spruce forests grow in the Leadville Limestone, Maroon Formation and portions of the Gothic Formation. Aspen groves generally favor areas underlain by jasperoid. Prominent talus slopes are derived from Sawatch Sandstone and jasperoid outcrops. Extensive mass wasting is indicative of areas underlain by the Belden Shale.

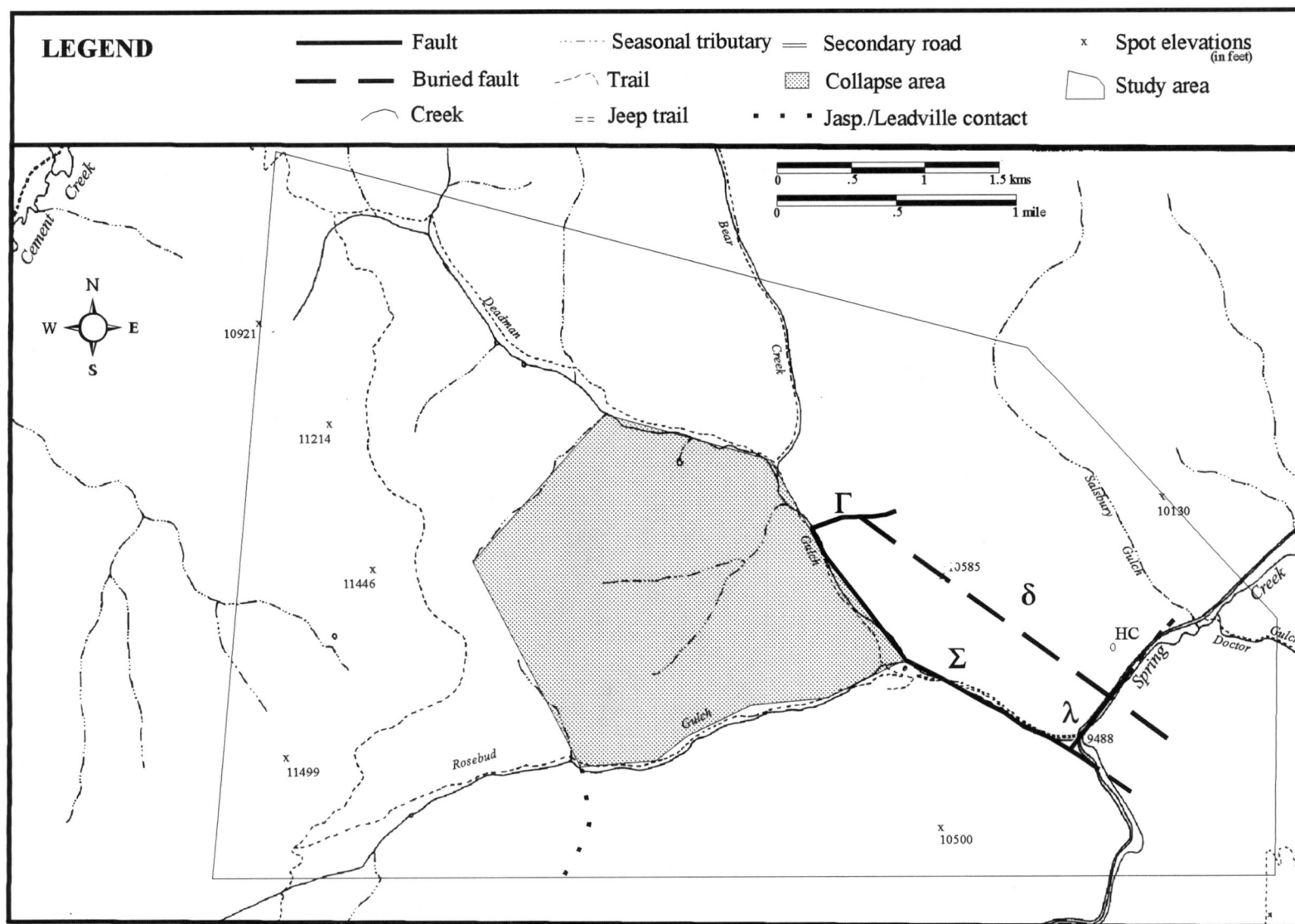


Figure 3: Stream drainage pattern, spot elevations, geologic and geographic highlights

STRATIGRAPHY

General Statement

The Sawatch Sandstone, Manitou Dolomite, Fremont Limestone and Chaffee Formation are the only units that can be measured accurately. These units are exposed in the southeastern portion of the study area and may have been thinned. To determine if thinning has occurred, measured sections must be compared locally. However, other Lower Paleozoic sections cannot be found nearby. Johnson (1944) and Bush and Bush (1973) measured these sections accurately in the study area and regionally. The section in Deadman Gulch is slightly thinner, but thinning due to development of the drape fold is only speculative. Upper Paleozoic formations cannot be accurately measured in the study area due to either absence of complete sections or covering of contacts by Holocene mass wasting deposits.

The study area lies within the Colorado Mineral Belt, where the Proterozoic basement complex, Leadville Limestone and Belden Shale are well known host rocks for various ore deposits. Exploratory drilling for uranium has been done in fractured Proterozoic granites near Jacks Cabin, 13 kms to the southeast (Goodknight, 1981). The Doctor Mine, just to the east of the study area, continues to produce zinc-lead ore (Fig. 2). Prospect pits are found in the study area; several are located within the drape fold.

Rock units in the study area range from Early Permian to Lower Proterozoic (Table 1). Four disconformities interrupt the lower

Paleozoic strata and a nonconformity separates the Proterozoic basement rocks from the Sawatch Sandstone.

Several Early Cretaceous and Tertiary rhyolite to dacite intrusions are exposed east and south of the study area. The closest intrusion is the Boston Peak Tertiary rhyolite (Fig. 2). To the northwest, the Crested Butte fine-grained granite laccolith intruded during the Middle Oligocene (Ouimette, 1991).

Underlying Cement Mountain (Fig. 2), the Leadville Limestone is several hundred feet thick. In the southern portion of the study area, a jasperoid takes the stratigraphic position of the Leadville Limestone (Fig. 1). Eastward from this contact, Leadville Limestone is not found. This jasperoid continues eastward into the drape fold, where it thins to a few tens of meters. The jasperoid deposition and/or replacement was concentrated in the Leadville Limestone, but locally affects portions of the Ordovician units and Chaffee Formation. Due to dissolving of the Leadville Limestone, the Belden Shale differentially collapsed near the center of the study area (Fig. 3), causing the jasperoid to form structures similar to sills and dikes of coal mining.

Deadman Gulch Jasperoid (informal) (Cretaceous?)

The jasperoid, a secondary microcrystalline quartz, is a void filling deposit and locally replaces Lower Paleozoic carbonates. The unit varies in thickness and is bound to the Paleozoic carbonates in and near the drape fold. The jasperoid is composed entirely of

microcrystalline quartz with rare accessory minerals. This unit will be described in detail later in this paper.

AGE	FORMATION	LITHOLOGY
Upper Permian to Middle Pennsylvanian	Maroon Formation	Maroon (color) cross-bedded conglomerate and sandstone with siltstone and shale beds
Middle Pennsylvanian	Gothic Formation	Micaceous and arkosic sandstone grading down to black fissile shale
Lower Pennsylvanian	Belden (Weber) Shale	Easily eroded, black to yellow-tan, fissile shale with thin, moderately fossiliferous limestone layers
---- Disconformity ----		
Mississippian	Leadville Limestone	Moderately fossiliferous, thin to thickly bedded limestone with local breccias, micrites, and dolomicrites
---- Disconformity ----		
Devonian	Chaffee Formation	Light to dark gray with mudstone, shale, and sandstone/sandy dolomite layers
---- Disconformity ----		
Upper Ordovician	Fremont Limestone	Massively bedded fossiliferous limestone
---- Disconformity ----		
Lower Ordovician	Manitou Dolomite	Generally light-gray, thickly bedded dolomite with chert nodules
Upper Cambrian	Sawatch Sandstone	Fine- to coarse-grained sandstone with scolithus tubes
---- Nonconformity ----		
Proterozoic	Basement crystalline rocks	Granite and granodiorite with local pegmatite and quartz-muscovite schist

Table 1: Outline of stratigraphic section

Paleozoic sedimentary rocks:***Maroon Formation*** (Early Permian to Middle Pennsylvanian)

The Maroon Formation is a thick-bedded, maroon (deep red/purple), cross-bedded conglomerate and arkosic sandstone with siltstone and shale beds. The formation, $2100 \pm$ meters (7000 feet) thick regionally, dates from Late Permian to Middle Pennsylvanian (Prather, 1982) and is the youngest major stratigraphic unit found in the study area. The unit is easily identified by the conglomeratic, massive, red to maroon outcrops. The Maroon Formation-Gothic Formation contact is a distinctive lithologic change from conglomeratic sandstones above to arkosic sandstones and shale beds below.

Gothic Formation (Middle Pennsylvanian)

The Upper Gothic Formation is an arkosic, tan-gray, gravelly sandstone with siltstone layers and 200 to 300 meters (600 to 1000 feet) thick. Rotated limestone and siltstone blocks (up to 10 meters long) were found in the Gothic Formation. The lower Gothic Formation grades downward to a black shale, making the Gothic Formation-Belden Shale contact somewhat arbitrary. The top of the Belden Shale is placed where black shale dominates sandstone in abundance.

Belden Shale (Lower Pennsylvanian)

The Belden Shale is a thinly-bedded, fissile, dark gray to black shale with minor, thin, light to dark gray, slightly fossiliferous (crinoid stems, trilobite pygidium, and genal spines) limestone and sandy shale

layers. Dark gray chert lenses are found locally. In upper Rosebud Gulch, the Belden Shale has a thickness of $200\pm$ meters (650 feet). Throughout the study area, slumping of the Belden Shale results in hummocky terrain and outcrops are rare.

The shale fails easily and readily absorbs fault displacements in the deeper, more brittle rocks. Thus, effects of faulting are obscured in the Belden Shale. Limestone layers in the Belden Shale have extension cracks filled with calcite veins (Fig. 4). These cracks show stress on the limestone layers and dip flattening can be observed.

Leadville Limestone (Mississippian)

The Leadville Limestone consists of three members (Kirk, 1931). The upper member is a thick-bedded fossiliferous limestone; the middle member consists of cherty micrite and dolomicrite; and the lowest member is a sandstone with local limestone and dolomite breccias, micrites, and dolomicrites. The lowest unit also contains a basal quartz sandstone. The Leadville Limestone is over 150 meters (500 feet) thick in upper Rosebud Gulch. Total unit thickness cannot be determined due to talus on the Leadville Limestone/Chaffee Formation contact and erosion of the Leadville Limestone/Belden Shale contact. In the Sawatch Range, Johnson (1944) found a maximum of 515 feet of Leadville Limestone at Fossil Ridge, 10 miles to the south. It is possible that the Leadville Limestone is thicker in upper Rosebud Gulch.



Figure 4: Dip of Belden (Shale) limestone bed decreases toward the east (right) along ridge east of Hill 10585 (Figs. 1, 3). Note calcite veins that fill extension cracks. View is to the north.

Chaffee Formation (Devonian)

The Chaffee Formation consists of the Dyer Dolomite and Parting Sandstone members (Prather, 1982). The upper half of the Dyer member contains a massive, cliff-forming, gray dolomite with blue-gray chert nodules and black, dolomitic limestone layers. The lower half encompasses numerous limestone, shale, and mudstone layers. The Parting Sandstone is a fine-grained sandstone with numerous shale, mudstone, and sandy dolomite layers. The unit is only six meters thick. Formation thickness totals 55 meters (180 feet) on the slope northeast of the Deadman Gulch and Rosebud Gulch junction (Johnson, 1944).

Fremont Limestone and Manitou Dolomite (Ordovician)

The Fremont Limestone (Upper Ordovician) is a gray, dolomitic limestone with abundant fossils (crinoid stems, shell fragments and corals). The Manitou Dolomite (Lower Ordovician) is a light-gray dolomite with white chert nodules and minor, thin, gray to white sandstone layers. Chert layers are found throughout, except at the top of the unit.

Like the Dyer Dolomite and Parting Sandstone, the Fremont Limestone and Manitou Dolomite are thin (20 and 65 meters respectively; Johnson, 1944) and are mapped as a single Ordovician unit. The Ordovician units were measured on the slope northeast of the Deadman Gulch and Rosebud Gulch junction.

Sawatch Sandstone (Cambrian)

Regionally, the Sawatch Sandstone includes any basal sandstone deposited on Proterozoic rocks overlain by Ordovician carbonates (Peterson, 1966). The Sawatch Sandstone, 80 meters (250 feet) thick in Deadman Gulch (Johnson, 1944), is a tan to brown, fine- to coarse-grained sandstone and white quartzite. The upper sandstone is lightly to strongly cross-bedded with red and purple staining due to weathering of glauconite. Slightly calcareous sandstone layers occur in the middle of the unit. The lower half of the formation is a white, coarse-grained sandstone. Nearing the basal nonconformity, the sandstone becomes "conglomeratic with well-rounded quartz pebbles" (Johnson, 1944; Lovering and others, 1978). Throughout the study area, the Sawatch Sandstone fractures into large, angular blocks, leading to extensive talus slopes. The unit was measured on the slope northeast of the Deadman Gulch and Rosebud Gulch junction.

Proterozoic rocks:

Crystalline basement rocks (Proterozoic)

Johnson (1944) describes the Proterozoic rocks in this area as a "quartz-mica schist." However, outcrops in lower Deadman Gulch are granite to granodiorite with local pegmatite veins and pods of quartz-muscovite schist. The schist is coarse-grained, with mica crystals reaching 1.5 cm in diameter. The basement "complex" dates at 2.3 billion years, giving an Early Proterozoic age in the Gunnison region (Brown, 1984).

STRUCTURE

The Paleozoic strata in lower Deadman Gulch form a continuous, non-faulted, sharp-hinged fold over basement granite (Fig. 5). Ductility in the strata near the upper bend (Fig. 6) indicates substantial confining pressures and warm temperatures during fold development. Locally, Paleozoic sandstone, limestone, and dolomite strata have been recrystallized. Portions of the Sawatch Sandstone, originally a fine to medium-grained sandstone, are altered to coarse-grained quartzite in the upper hinge. Faults and fractures in the basement crystalline rocks channeled deep, hydrothermal waters which dissolved the Leadville Limestone, the Chaffee Formation and portions of the Ordovician units (Lovering, 1972). Some replacement occurred. At Doctor Gulch mine (Fig. 2), jasperoid replacement of brecciated Upper Paleozoic limestone is noted by Heyl (1964).

Distribution of units

In upper Deadman and Rosebud Gulches, the Maroon Formation, Gothic Formation, Belden Shale, Leadville Limestone and Ordovician units have a general east-west strike with a gentle to moderate dip (11° - 23°) to the north-northeast (Fig. 1). Recent mass wasting has rendered many strike and dip measurements misleading and ultimately useless (Figs. 7 and 8).

The Maroon Formation in the northern portion of the study area continues beyond Bear Creek to northeastern Cement Creek canyon (Figs. 1 and 2). A sharp change from spruce forests to aspen groves



Figure 5: Deadman Gulch drape fold. At bottom left, the Sawatch Sandstone is near vertical. At center, the dip is about 45° . At upper right, the dip of the Sawatch Sandstone is about 25° . Field at upper left is underlain by the Belden Shale (in Doctor Gulch). View is toward southeast. Note talus slopes. Stratigraphic "up" is to left.

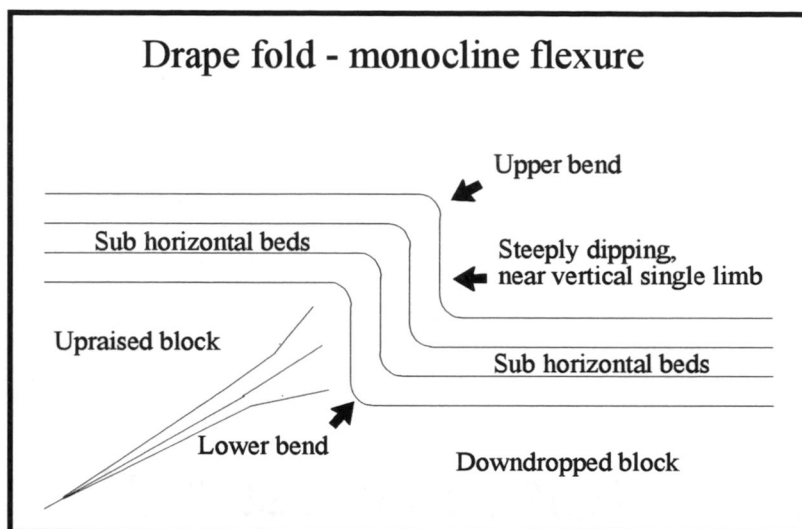


Figure 6: Terminology and generalized cross section of a drape fold.

sharply defines the Gothic Formation-Maroon Formation contact (Fig. 9).

From Salsbury Gulch to Bear Creek, the Belden Shale-Gothic Formation contact parallels the Gothic Formation-Maroon Formation contact. However, deviation from a simple pattern begins just west of the collapse area (Fig. 3). It appears that the Belden Shale thickens through the center of the study area (Fig. 1). However, this is an illusion probably created by the collapse of the Leadville Limestone (and possibly lower carbonates?) beneath the Belden Shale. The Belden Shale-Gothic Formation contact swings south toward Rosebud Gulch and turns northwest between Hills 11446 and 11499. Gothic Formation strikes and dips vary tremendously along the ridge from Hill 10921 to Hill 11446 due to rotated blocks. The Leadville Limestone only outcrops in the southwestern portion of the study area and is not found



Figure 7: Slumped terrain of Belden Shale. View is to east along Deadman Gulch. Bear Creek is at top right.



Figure 8: Large slump block of Belden Shale. View is east from Hill 11499. Lower Deadman Gulch (with horizontal Lower Paleozoic strata) is just beyond the slump block.



Figure 9: Gothic Formation-Maroon Formation contact coincides with treeline change from aspen to spruce. Grassy area is mostly underlain by Belden. View is north looking up Bear Creek from Deadman Gulch. Boston Peak, an early Tertiary rhyolite intrusion, is at top of frame.

in the drape fold. Thick sections of the Leadville Limestone form large cliffs on the south side of Rosebud Gulch near East Cement Mountain (Fig. 1 and 10). The jasperoid/Leadville Limestone contact (Fig. 1) in the south has no particular characteristic to determine inclination. Conversely, the change is abrupt and sharp. The Chaffee Formation is only found northeast of Fault Σ (Fig. 3). To the southeast the Chaffee Formation has been dissolved and/or replaced by the jasperoid. The Ordovician units are only found in the drape fold and as a thin outcrop in Rosebud Gulch. The thin exposure consists of only Manitou Dolomite. The Fremont Limestone is not found and was also dissolved and/or replaced by jasperoid.



Figure 10: Massive Leadville Limestone cliff. Picture taken approximately 0.5 miles east of Hill 11499 looking to the south-southeast.

DEVELOPMENT OF DRAPE FOLDS

Ductile drape folds involve numerous geometric and mechanical complexities. However, as Brown (1982) pointed out in describing drape folds of the Front Range:

"That the layered carbonates can conform to the shape of the forcing member without [appreciable] thinning, faulting, or the creation of subsidiary folds is an observational fact," which "...must be accepted as part of reality."

Chamberlin (1919, 1923) was perhaps the first to generally apply compressive deformation to the Colorado Rocky Mountains. Since then, countless ideas have been proposed concerning orientations of the basement faults. Several authors emphasize vertical faults with Paleozoic strata detachment on the upraised or downdropped blocks (Prucha and others, 1965; Tweto, 1975; Matthews, 1978). Others favor horizontal compression and low-angle, basement thrusting (Berg, 1962; Blackstone, 1963; Brown, 1982, 1984, 1988).

The brittle/ductile nature of the basement rocks and overlying strata depends on temperature and pressure (Stearns, 1970, 1971; Davis, 1978; Matthews and Work, 1978; Reches, 1978; Stearns and Stearns, 1978). Massive igneous and metamorphic rocks act brittly to depths of 8-12 km (Stearns, 1970). The possible responses to the basement fault are: ductile with thinning, ductile without thinning, or brittle with detachment (Stearns, 1978). Burial depths of 5-7 kms suppress brittle cracking and enhance ductility in sedimentary rocks (Handin and others, 1976). At the time of the Laramide orogeny, 5 kms of overburden (about 17000 feet from the top of the Mesaverde group to the Belden Shale-

Leadville Limestone contact) could have been present above the lower Paleozoic strata (Table 2). The Laramide orogeny is probably the only mountain building episode when the overburden was thick enough for the Paleozoic strata to ductily deform.

AGE	FORMATION	REGIONAL THICKNESS (FT)
Upper Cretaceous	Mesaverde sandstone	1500
Upper Cretaceous	Mancos shale	5000
Lower Cretaceous	Dakota sandstone	120-300
Lower Cretaceous to Middle Jurassic	Morrison	320-380
Middle to Lower Jurassic	Junction Creek, Wanakah, Entrada	0-390
Upper Permian to Middle Pennsylvanian	Maroon sandstone	0-7000
Middle Pennsylvanian	Gothic sandstone	2500
Lower Pennsylvanian	Belden (Weber)	0-500
----- Disconformity -----		
Mississippian	Leadville limestone	210-545
----- Disconformity -----		
Devonian	Chaffee	300
----- Disconformity -----		
Upper Ordovician	Fremont limestone	45-75
----- Disconformity -----		
Lower Ordovician	Manitou dolomite	140-250
Upper Cambrian	Sawatch sandstone	130-300

Table 2: Phanerozoic formation thicknesses during the Laramide orogeny

Model tests under confining pressures show that shear displacement along bedding planes and ductile flow within a unit may also aid in the formation of drape folds (Brown, 1982; Friedman and others, 1976; Stearns, 1978; Stearns and Weinberg, 1975). Kinematic experiments found similarities between laboratory experiments and field

observations (Davis, 1978; Weinberg, 1978; Chester, 1985; Chester and others, 1988). Field examples and laboratory experiments implicate compressional forces in development of such folds.

The forcing member determines the overall fold orientation. Brown (1982) firmly believes that high-angle reverse to low angle thrust faults are the sole causes of drape folds. It is imperative to understand that overall horizontal shortening (crustal compression) must occur for drape folds to form. Therefore, a thrust fault is thought to be the forcing member of the Deadman Gulch drape fold.

DEADMAN GULCH DRAPE FOLD

Approximately 450 meters northeast of the Deadman Gulch-Spring Creek junction, the lower Paleozoic strata drape over an upper basement fault block onto a lower fault block in a non-faulted, ductile fold (Figs. 11, 12). On the exposed vertical limb, the Sawatch Sandstone dip is vertical to slightly overturned (Fig. 12).

The drape fold and associated faults are not shown on published structural and geologic maps, probably for two reasons: (1) the fold is a local feature; and (2) the faults (except fault Γ) are hidden beneath lower Paleozoic rocks and talus (hence, faults cannot be directly observed). Belden Shale through Sawatch Sandstone strata are draped over the upraised fault block in a single, near vertical limb. Slippage along bedding planes in the Belden Shale allows flexure movement. Thus, Belden Shale dips are not as high as in the lower Paleozoic strata

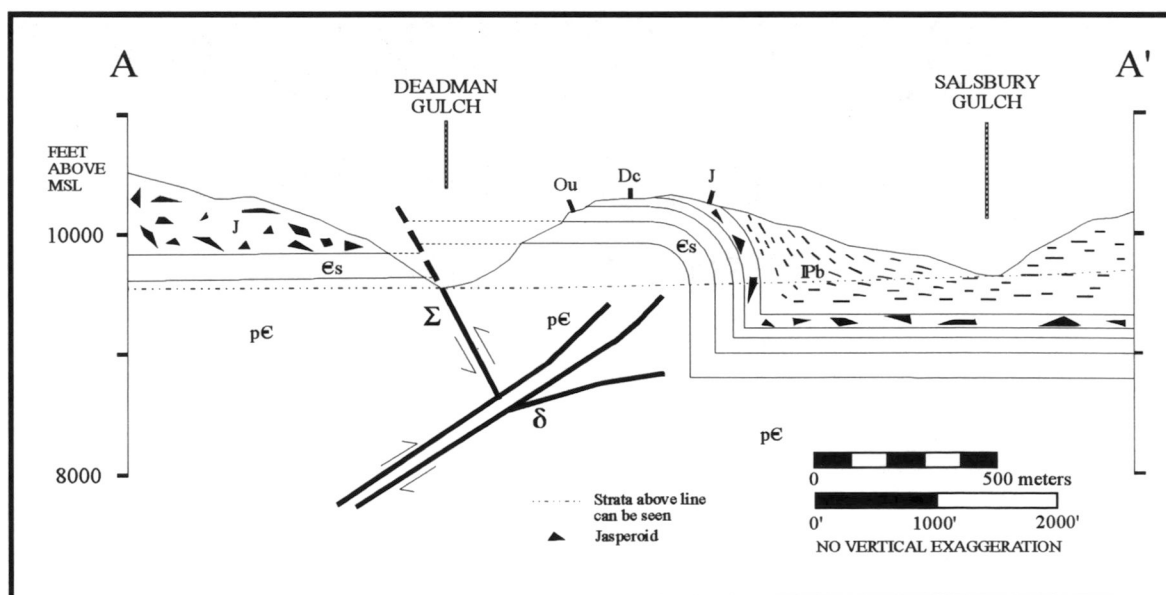


Figure 11: Cross section A-A', Deadman Gulch, Gunnison County, Colorado



Figure 12: Vertical Sawatch Sandstone at Spring Creek road. Stratigraphic "up" is to left. Talus blocks cover contact with Proterozoic basement and Ordovician units. View is toward southeast.

and they flatten abruptly just northeast of the drape fold (Fig. 1 and 11).

Due to the ductile reaction of the Paleozoic strata, basal units of the Sawatch Sandstone lie against the Proterozoic basement. The basement fault modified the nonconformity. It should be noted that the present-day contact was created through tectonics, not by erosion and deposition. The Sawatch Sandstone strike, N53W, is parallel to the bent stratum fault and is similar to trends of major faults in the region (Lovering, 1966; Tweto, 1976). Additionally, if the fault is projected to the northwest, the trace generally coincides with Deadman Gulch.

Faults Σ and λ are subsidiaries of fault δ (Fig. 3). Fault λ is located at the entrance to Deadman Gulch and strikes northeast along Spring Creek canyon. The Proterozoic basement-Sawatch Sandstone contact on northwest and southeast sides of Spring Creek are sub-horizontal but the southeast side is approximately 200 feet higher (Fig. 1); this represents offset along Fault λ .

In models, Chester and others (1988) found that ductile drape folds driven by basement thrusts develop triangular fault blocks in the upraised basement tip, resulting in splayed faults (Fig. 11). The closest basement rock outcrops are 50 meters southwest of the drape fold (Fig. 1) but the Proterozoic basement-Sawatch Sandstone contact is covered by talus.

Fault Γ (Fig. 3) is a tear/oblique fault at the northwest end of the drape fold. On the south side of the tear fault, the lower Paleozoic section is observed undisturbed. The north side of the fault is a slope underlain by Belden Shale. The fault attitude is high angle as it does not

vary in direction due to topography. The fault follows the small valley upslope toward the ridge between Salsbury Gulch and Deadman Gulch. The tear fault continues eastward past the northwest end of the basement thrust because it effects part of the Belden Shale. The intersection of faults is indicative of a drape fold corner (northwestern basement thrust limit).

BED LENGTH AND DUCTILITY

As a drape fold develops, a new length of vertical Paleozoic strata is created. Balancing such a section can be done by detachment and opening a gap, by thinning (possibly associated with bed plane shearing) or by shortening of the entire system.

Figure 13 is a generalized cross section showing drape fold possible solutions for bed length problems. In order for length -y- to be created, one of the following must occur:

1. detachment allows the subhorizontal beds on the upraised (or downdropped) block to move toward the fold (Fig. 13a, 13b);
2. normal faulting occurs in the upper bend (Fig. 13c);
3. thinning of the subhorizontal beds occurs (Fig. 13d);
4. overall horizontal shortening (including the forcing member) occurs (Fig. 13e).

With a 45° fault in the forcing member, length -y- will equal length -x- (Fig. 13e). With a higher angle, thinning must transpire. Low angle thrust faults in the forcing member may actually increase the thickness of the steeply dipping beds.

Figure 13e is the most likely choice for the Deadman Gulch drape fold. Thrusting is common in the area and detachment on the upraised block is not observed. In Deadman Gulch, the material eroded from the gulch is not sufficient to provide enough material to merit length -y- as seen in Figure 13a. Figure 13b cannot be ruled out as the lower subhorizontal beds cannot be observed. However, sliding the lower Paleozoic strata horizontally and bending them to vertical hardly seems

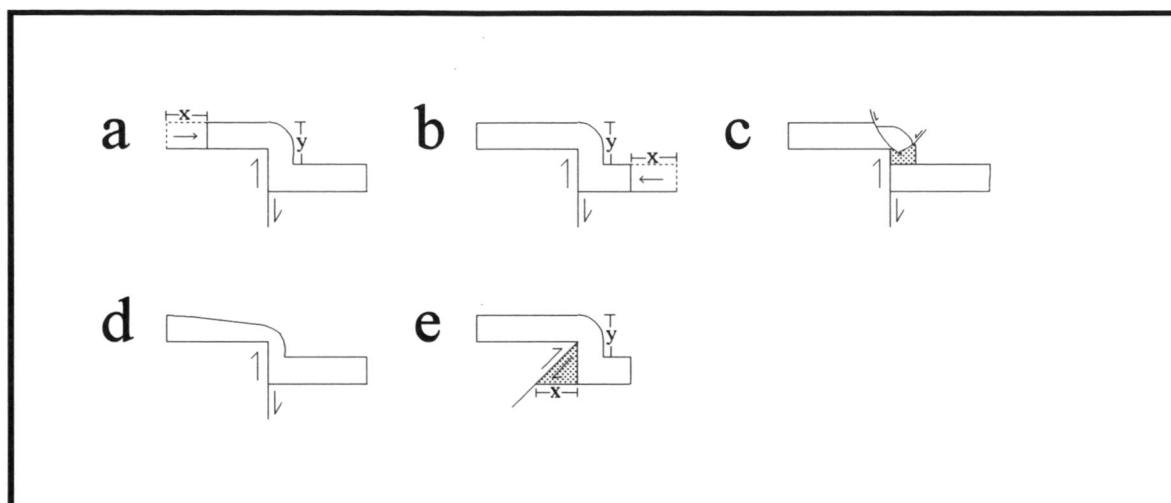


Figure 13: Ductility versus detachment used to fulfill bed length problems. In figures a and b, detachment coupled with horizontal movement of the overlying strata solves the equation $x=y$, where y is the new length. Figure c involves normal faulting. Figure d uses thinning in the hinge with ductile strata. Figure e has a fault dipping 45 degrees in the basement rock. With a fault dipping 45 degrees, $x=y$. With a higher angle fault, the vertical section will be thinned. With a lower angle, the vertical section may thicken.

possible. Normal faulting in the upper bend (Fig. 13c) is not observed in the Deadman Gulch drape fold. Comparison of measured sections at the vertical cut in the fold does not reveal thinning in the hinge (Fig. 13d).

Stearns (1971) observed no thinning in the upper bend of the drape fold at Rattlesnake Mountain. Instead, he found rigid, detached, rotated blocks that satisfied the bed-length problem. Stearns and Stearns (1978) found bed-thickness changes and deformation of grains in the Madison Formation (carbonate) at Rattlesnake Mountain, Montana. In other cases, such as the Deadman Gulch drape fold, the lower Paleozoic strata evidently deformed in a ductile manner without detachment.

To accommodate volume created beneath the rising fault tip, the assumed thrust fault (δ) splays into the upper hinge of the fold (Fig. 14). As the fault displacement increases, a void is created above the down-dropped block. The upraised block tip continually breaks off due to geostatic pressure and the fragments are displaced in the void. In the splayed fault area, the Proterozoic basement-Sawatch Sandstone contact is covered by Sawatch and jasperoid talus, so the dip of Fault δ cannot be determined.

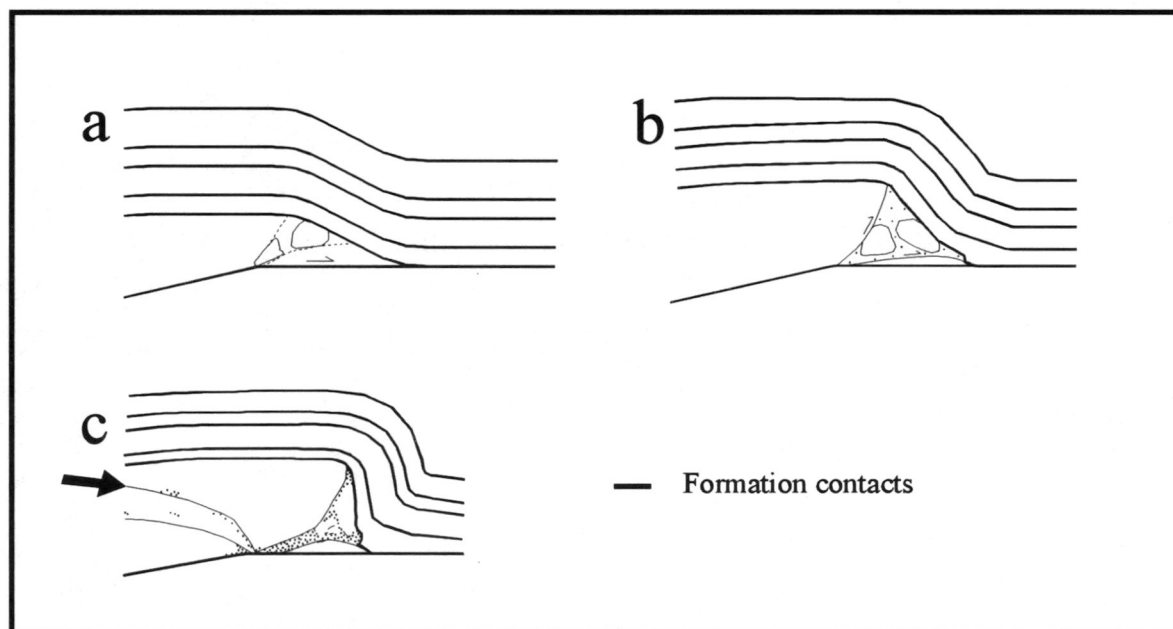


Figure 14: Line drawings showing the development of the basement surface through fracture, imbricate faulting and rotation of basement blocks between zones of cataclasis. During development, the upraised block tip becomes blunt. The crushed and rotated material fills the void. Note backthrust faults in upraised block (arrow). (From Chester and others, 1988)

JASPEROID

Jasperoid (informal) was first described by Spurr (1898) as "... a rock consisting essentially of cryptocrystalline, chalcedonic, or phenocrystalline silica, which has formed by the replacement of some other material, ordinarily calcite or dolomite." Lindgren (1901) includes rocks near shear zones with "...many tiny quartz grains [that] first appear scattered through the rock," and with continued silicification, the "...slender crystals multiply." Duke (1959) defines a jasperoid as "any rock which is composed mostly of secondary silica." Lovering (1972) further simplifies the definition by limiting jasperoid to rocks containing at least 50% replacement silica, but added that it must be "an epigenetic siliceous replacement of a previously lithified host rock." In the case of the Deadman Gulch jasperoid, all of the above apply.

Dissolving of the carbonates and deposition of jasperoid is caused by silica-enriched, hydrothermal waters moving through a permeable rock unit (Lovering, 1972). Susceptibility to dissolving is associated with collapse of solution cavities and hydrothermal activity related to fluid flows along major fault conduits (Lovering, 1972). Jasperoid is commonly deposited along bedding planes and in joints, caverns and collapse breccias in limestone and dolomite. Dolomite is more resistant to dissolving than limestone. In the Deadman Gulch area, the Leadville Limestone, Chaffee Formation, Fremont Limestone and Manitou Dolomite were susceptible to dissolving for several reasons:

- Local intrusions (such as those to the east and northeast) likely generated hydrothermal circulation in the surrounding

wall rocks;

- Carbonates are particularly susceptible to dissolving due to chemical composition;
- Laramide-age fractures in Proterozoic rocks allowed deep hydrothermal circulation; rising waters focused along fractures.
- The Leadville Limestone was more prone to dissolving due to precursor solution cavities (Johnson, 1944; Lovering, 1972); the exposed surface area is increased, allowing further dissolving of carbonate and silica precipitation.

Regional Jasperoids

The Leadville Mining District is within the central Colorado Jasperoid Province (Fig. 15) and ore deposits are commonly associated with jasperoid bodies. Dissolving of units and/or replacement by jasperoid in this area is most common in the Leadville Limestone, but replacement has also occurred in the Dyer and Manitou Dolomites (Lovering, 1972). In the Gilman District (Fig. 15), the entire Leadville Limestone and Dyer Dolomite have been replaced by jasperoid (Lovering and others, 1978).

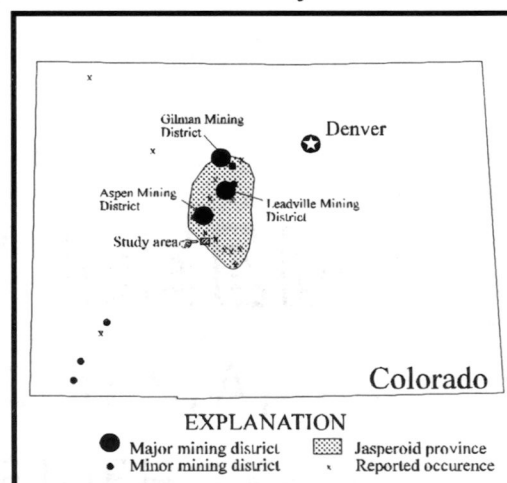


Figure 15: Jasperoid bearing localities in Colorado (from Lovering, 1972)

Secondary silica is commonly misidentified as secondary dolomite and/or limestone, resulting in overestimates of dolomite and limestone abundance and *underestimates* of secondary silica (Johnson, 1944). Likewise, the Deadman Gulch jasperoid has been misidentified as Leadville Limestone on Hill 10500 (Figs. 1, 3) in Emmons (1894) and

Hill 10585 in Emmons (1894), Johnson (1944) and Bush and Bush (1974).

In the Leadville Mining District, minerals associated with jasperoid include barite, calcite, dolomite, kaolinite, limonite, pyrite, sericite, sphalerite, tourmaline, and zircon. Less common minerals include ankerite, manganese oxides, opal, microcline, orthoclase, plagioclase, siderite, smithsonite, sphene, stibnite, tremolite and wulfenite (Lovering, 1972). Pyrite, barite and sphene were identified in the Deadman Gulch jasperoid from thin sections. Accessory elements include arsenic, beryllium, germanium, manganese, niobium, antimony, scandium, tungsten, and yttrium (Lovering and Heyl, 1980). The minor minerals and accessory elements are generally distributed evenly throughout jasperoid matrix or can locally concentrate near veins.

In early articles, "chimney" deposits described the sharp, tall structures created by jasperoid bodies (Lovering and others, 1978; Lovering and Heyl, 1980). These bodies are believed to be dike deposits that have resisted erosion. The two "chimneys" observed in the Deadman Gulch area are associated with collapse of the Leadville Limestone (Fig. 16).

Deadman Gulch jasperoid

In the study area, jasperoid takes the stratigraphic position of the Leadville Limestone and portions of the Ordovician units and Chaffee Formation. The jasperoid is interpreted as a local, fault-related, hydrothermal deposit, directly associated with the Deadman Gulch drape



Figure 16: "Chimney" of jasperoid that has "punched" through the Belden Shale as the Leadville Limestone collapsed. Outcrop is approximately 20 meters high.

fold. The unit is restricted to the Leadville Limestone eastward from a north-south trending line situated about mid-way between Hill 10585 and Hill 11499 (Fig. 1 and 3).

In addition to the Leadville Limestone, the Chaffee Formation and Ordovician units were dissolved and/or replaced southwest of Fault Σ (Fig. 3). No evidence can be found to determine why the Chaffee Formation and Ordovician units were affected only in this area. However, basement faults may have focused silica-rich, hydrothermal waters into the area. The Belden Shale, having a low permeability and weak (macroscopic, ability to absorb fault movement) mechanical characteristics, acted as an important barrier to fluid movement, forcing the rising waters to move laterally through the permeable and soluble carbonates.

Under Hill 10500, jasperoid is about 190 meters (600 feet) thick (note that this includes Chaffee Formation and Ordovician units). In the fold, jasperoid is 35 meters (115 feet) in the upper bend of the fold (does not include dissolving and/or replacement of the Chaffee Formation and Ordovician units). This apparent "thinning" is either due to differential dissolving and collapse of the Leadville Limestone or due to differential thickness of the Leadville Limestone.

West of the Rosebud-Deadman Gulch junction and north of Rosebud Gulch (Fig. 3), jasperoid forms sill-like and dike-like bodies (Fig. 17). During dissolving of the Leadville Limestone and jasperoid deposition, open space areas were created. Thin cavern roofs encouraged subsidence, allowing pillars of jasperoid (already formed) to

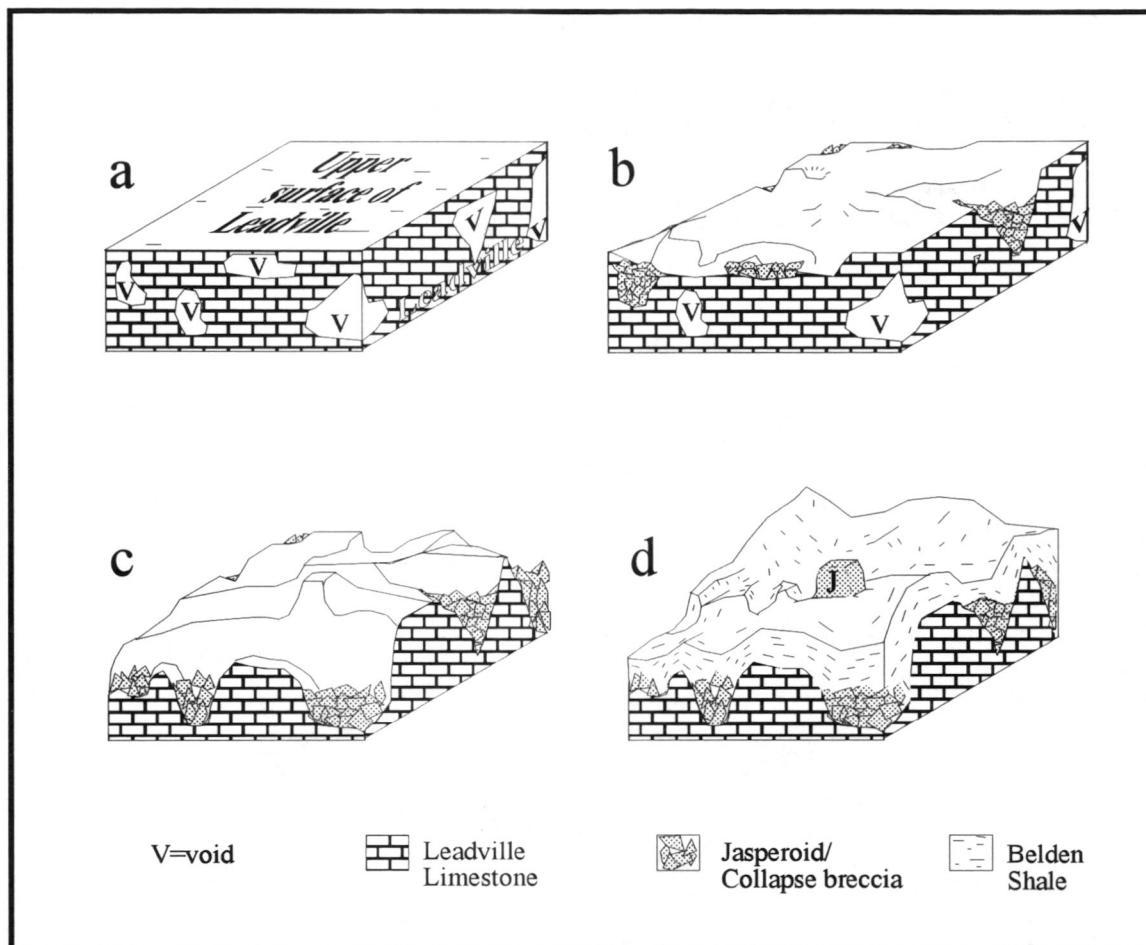


Figure 17: Collapse within the Leadville Limestone. In a, b and c, the Belden Shale is not shown so the upper surface of the Leadville Limestone is visible. Figure D superimposes the Belden Shale on the Leadville Limestone. Note that jasperoid (replacing the Leadville Limestone and filling void spaces before or during collapsing), in effect, "punches" through the Belden Shale.

"penetrate" the collapsing Belden Shale. Volume loss is more or less proportionate to the amount of vertical subsidence. The Belden Shale outcrops are distorted and slumped in the collapse area (Figs. 3, 7). The collapse gives the illusion that the Belden Shale is thick.

Formation of solution cavities in the upper Leadville Limestone during subaerial exposure and before deposition of the Belden Shale is

well documented (Johnson, 1944). However, total volume of dissolving (pre-Belden Shale deposition) has not been recorded. Jasperoid deposition probably occurred either before or during basement thrusting.

Sedimentary dolomite crystals, relict sedimentary structures and fossils are rarely preserved in jasperoid formed by replacement. These primary structures, found on the slopes of Hill 10500 (Figs. 1, 3) show that Ordovician units and Chaffee Formation were replaced (not dissolved and later deposition of jasperoid). To the north, an outcrop of the Manitou Dolomite (Lower Ordovician) is found in lower Rosebud Gulch, indicating less hydrothermal water circulation (it is presumed that the Fremont Limestone, Upper Ordovician, has been either replaced or dissolved). The Belden Shale unconformably lies on the Manitou Dolomite (Figs. 1 and 18). Although the Belden Shale lies on the Manitou Dolomite, faulting is not observed. Dissolving the Leadville Limestone, Chaffee Formation and the Fremont Limestone would allow the Belden Shale to drop onto the Manitou Dolomite.

There are two distinctive types of jasperoid. The first type consists of very angular, unsorted, breccia fragments in an open-space filling, microcrystalline silica matrix. This breccia jasperoid is restricted to fault zones. Fragment and matrix support is evident. Matrix color varies from light tan to light gray; locally, the matrix is red. Fragments are generally light to dark gray. The second type, entirely microcrystalline quartz, is more likely open-space filling rather than replacement of a carbonate. This solid jasperoid is only found in

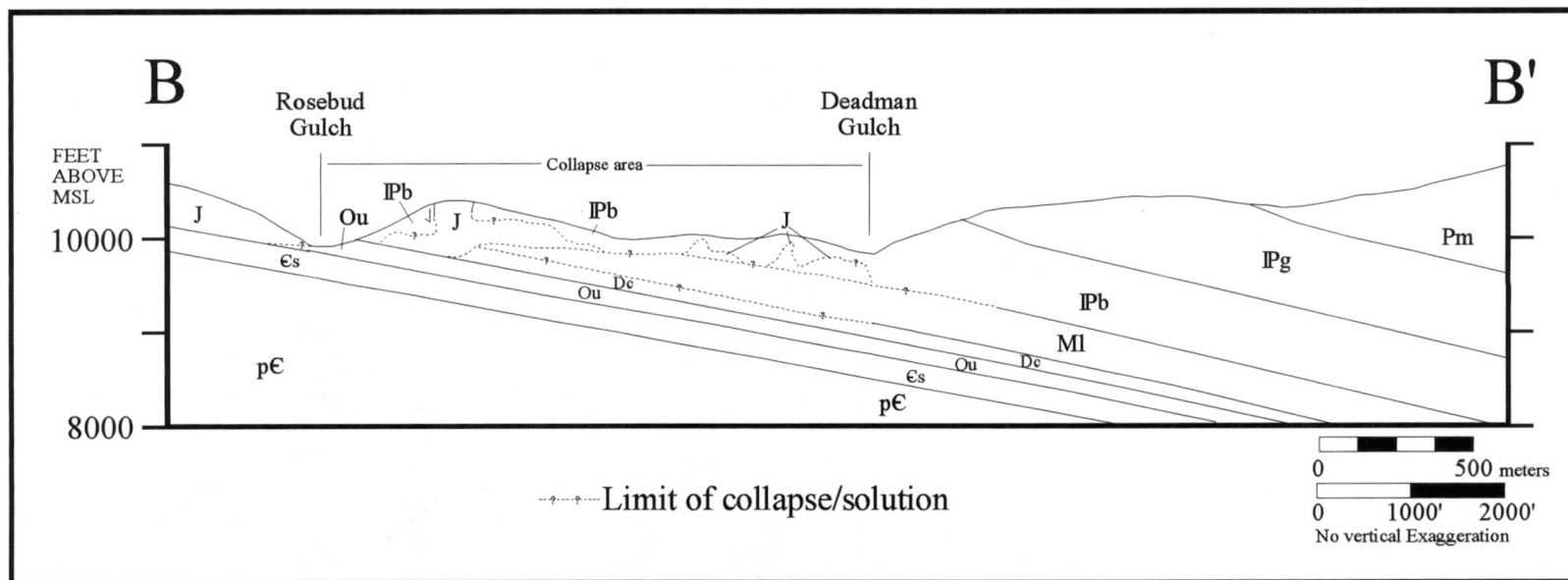


Figure 18: Cross section B:B'. Leadville Limestone (MI), Chaffee Formation (Dc) and portions of the Ordovician units (Ou) have been solutioned. The Belden Shale (IPb) has collapsed in some of the void spaces. Jasperoid (J) was probably deposited before or during solution and collapse.

the collapse area and is brick red in color, probably from pyrite oxidation. Both types can be slightly porous.

Thin sections reveal that matrix and breccia fragments are comprised of secondary microcrystalline quartz (Fig. 19). Rare crystals of calcite, barite, pyrite and sphene are observed. Relict fossils and textures can be identified in jasperoid samples taken from the northeast and east slopes of Hill 10500 (Fig. 3). Less than one percent of jasperoid samples revealed relict sedimentary textures or fossils. Fossil remains preserved in the jasperoid include trilobite fragments, gastropods, ostricods(?), blastoids(?) and crinoid stems(?) (Figs. 20-22). Replacement has only preserved exterior outlines, so individual species cannot be identified. These relict fossils and textures show that some mineral replacement occurred (silica for limestone/dolomite).

At least four fracturing-vein filling events can be identified (Figs. 23-24) in the jasperoid. First stage fracturing forms the major fragment of limestone (Fig. 24a). During the second stage, fracturing and vein fillings crosscut the fragment (Fig. 24b). In stage three, the fragment is broken into two pieces and microcrystalline quartz infills between the fragments (Fig. 24c). During the final stage, a large fracture is filled with quartz, cross-cutting earlier stages (Fig. 24d). Replacement in the fragments may occur during (or between) any of these stages.

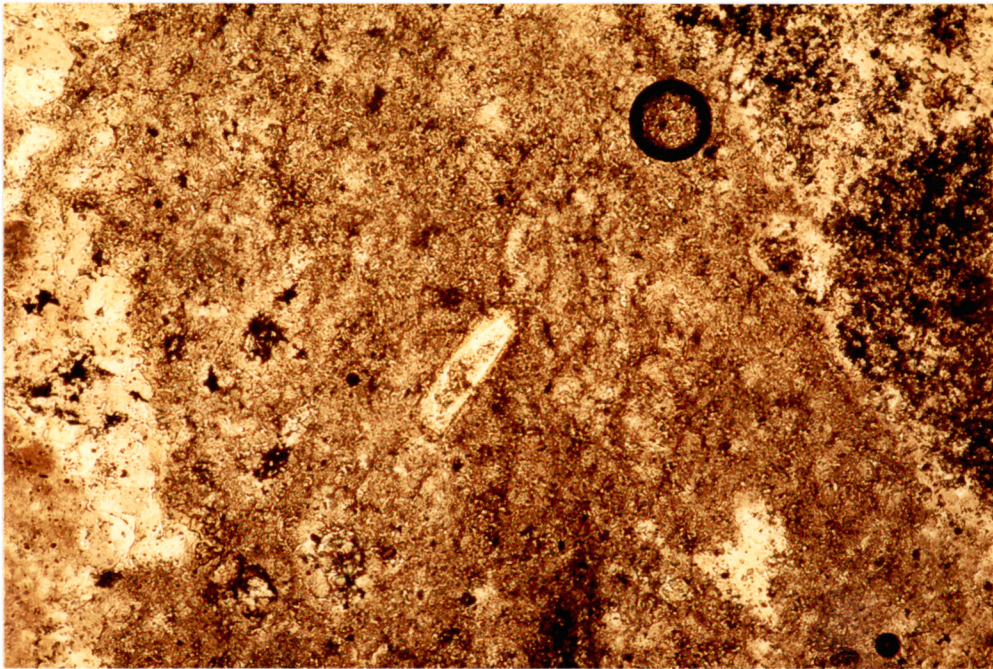


Figure 19: Secondary microcrystalline quartz of jasperoid. Note large euhedral quartz crystal (near center of frame). Frame width: 1.24mm

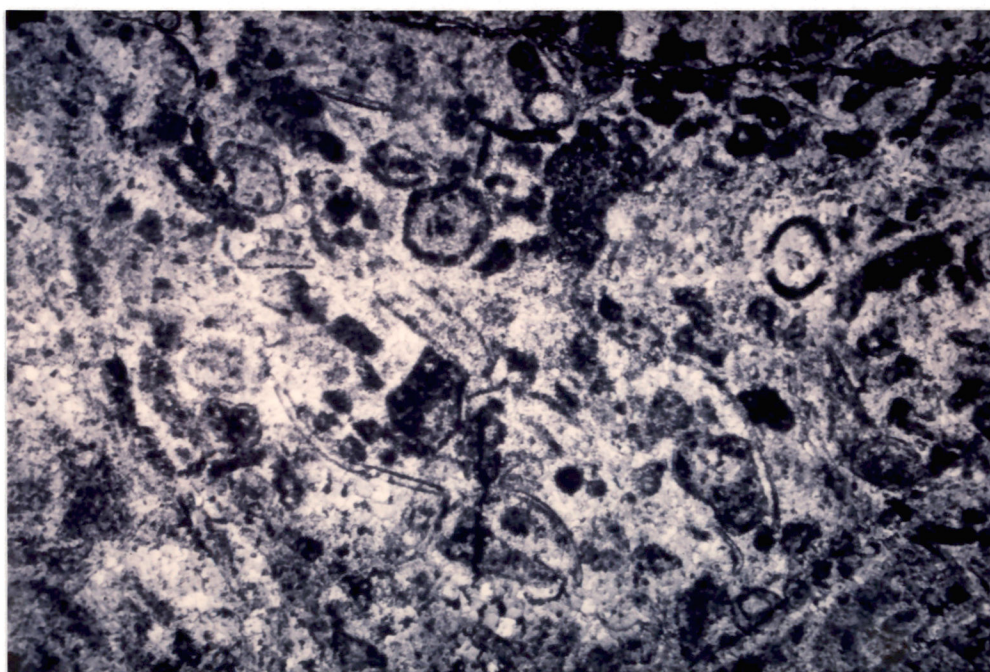


Figure 20: Fossil fragments (crinoid stems, brachiopods? and ostricods?) preserved in jasperoid breccia fragment. Frame width: 3.08mm

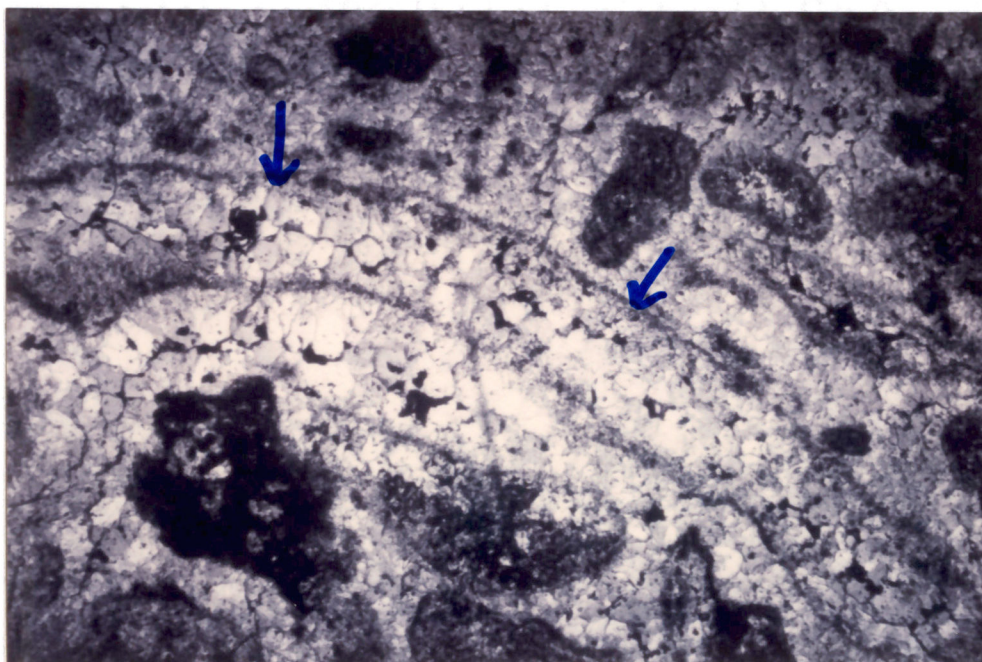


Figure 21: Trilobite pleura preserved in jasperoid breccia fragment.
Frame width: 3.08mm

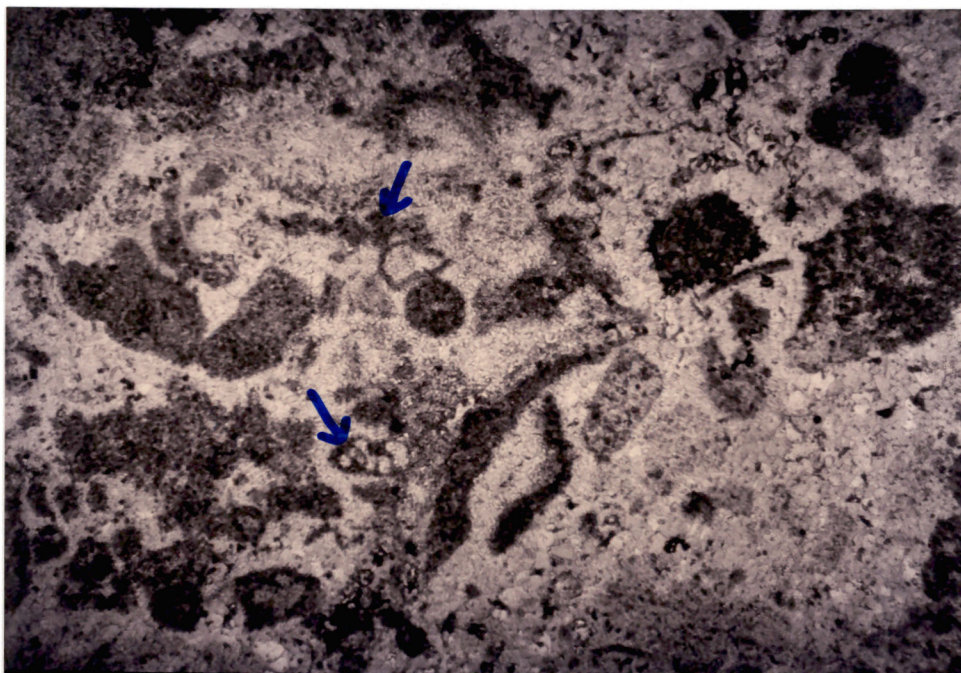


Figure 22: Gastropod remnant (upper arrow) and foraminifera (lower arrow) in jasperoid breccia fragment; most likely replaced Fremont Limestone (Upper Ordovician). Frame width: 3.08mm

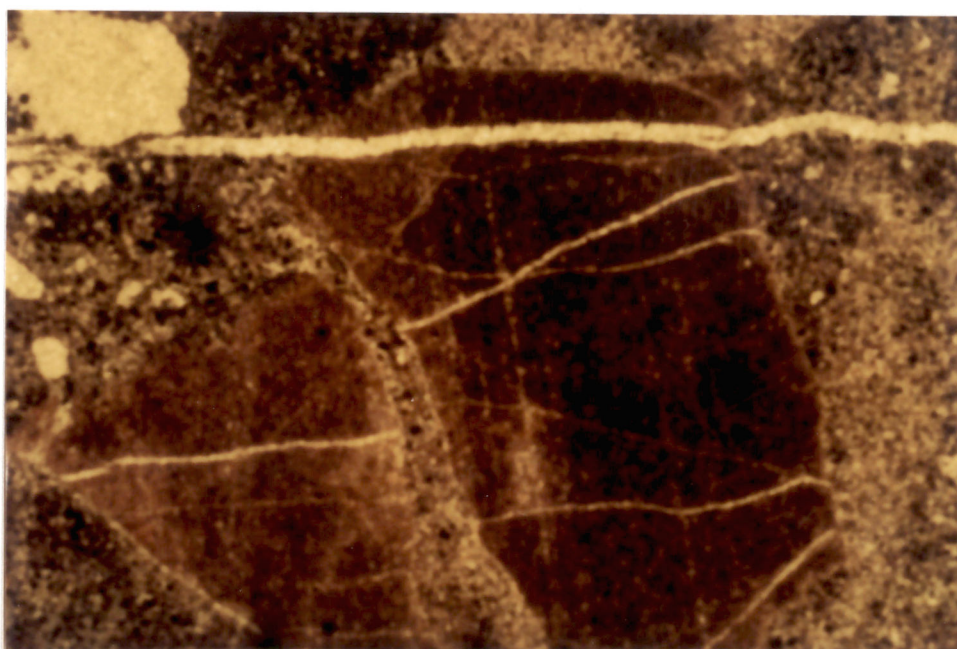


Figure 23: Formation of jasperoid fragments. 1) Breccia fragment is made; 2) quartz veins are created in fragment; 3) breccia fragment is broken and space between fragments is filled with microcrystalline quartz; 4) large vein cross cuts fragment and penetrates matrix between fragments. Note relict sedimentary layers in fragment. Frame width: 3.08mm

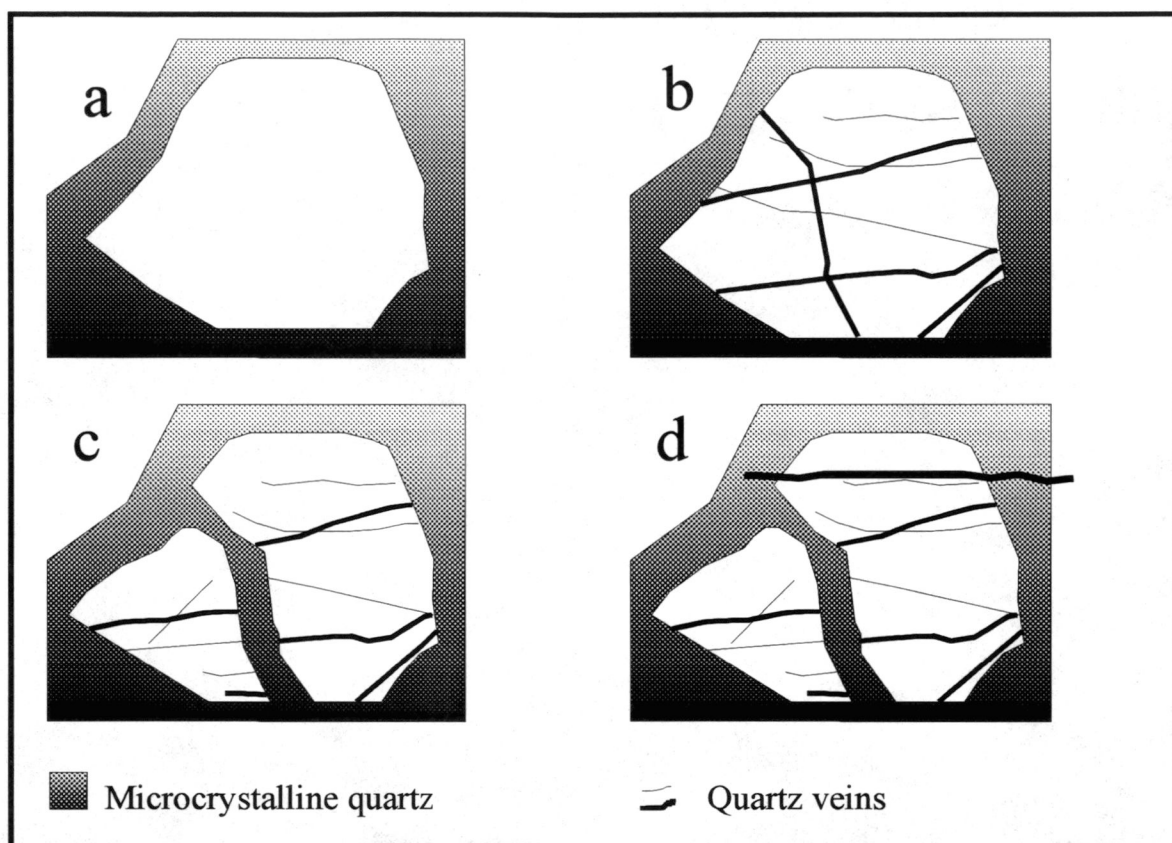


Figure 24: Fracture-void filling by jasperoid (explanation of Figure 23).
 a) breccia fragment is made; b) small fractures are made and enfilled by quartz;
 c) fragment is broke in half and void filled by quartz; d) large fracture is made
 and enfilled by quartz.

GEOLOGIC HISTORY

Early Proterozoic basement rocks are granite/granodiorite with local schists. Extensive erosion ended with deposition of the Sawatch Sandstone, creating the Cambrian-Proterozoic unconformity.

From Early Cambrian to Early Pennsylvanian time, transgressive and regressive seas deposited shoreline sandstones, offshore carbonates and marine shales over the Proterozoic craton. Changing sea levels and vertical regional tectonic movements resulted in several disconformities. During the Middle Pennsylvanian micaceous and arkosic sandstones were deposited in regressive seas. Regression continued into the Late Permian, allowing continental cross bedded conglomerates, sandstones and siltstones to be deposited. During the early Mesozoic, continental conditions prevailed with eolian deposition (Entrada Sandstone). Fluvial and lake deposits (Morrison Sandstone) accumulated during the Jurassic. Marine shoreline conditions again returned during the Early Cretaceous (Dakota Sandstone) and extensive transgression during the Late Cretaceous allowed for deposition of the Mancos Shale.

During the Laramide orogeny (Late Cretaceous to Early Paleogene; Hamilton, 1988), compression placed stress on the basement, resulting in an assumed thrust fault. Overburden pressures and warm temperatures prompted the Paleozoic strata to react ductily to the basement offset. Fluid pressure from hydrothermal waters may have aided in lowering stress. The thrust in the Proterozoic basement pushed the hanging wall over the foot wall, creating splay faults in the hanging wall tip. Simultaneously, the silica rich waters began circulation

through the porous, permeable Leadville Limestone. Hydrothermal action waned, reducing pore pressure. Solution channels and caverns collapsed, dropping the overlying Belden Shale onto patches of Leadville Limestone and jasperoid. Pore pressure again returned. Continued fracturing and silica precipitation developed the jasperoid and eventually the entire limestone unit was dissolved.

During basement thrusting, a subsidiary fault (Σ ; Figs. 3, 13) developed, dropping the upraised thrust block. The fault is hidden by alluvium of Spring Creek, but is most likely a back thrust.

CONCLUSIONS

1. The Deadman Gulch drape fold, a ductile, continuous monoclinial flexure, developed due to either a buried thrust or reverse fault (compressive forces);
2. Due to ductility requirements of the Lower Paleozoic strata, the Deadman Gulch drape fold most likely developed during the Laramide orogeny;
3. The northwest end of the drape fold terminates by an east-west trending tear/oblique fault; the southeast end of the drape fold is buried beneath Upper Paleozoic strata;
4. Locally, the Leadville Limestone, Chaffee Formation, Fremont Limestone and Manitou Dolomite have been dissolved by hydrothermal waters. Jasperoid deposited in void spaces;
5. Jasperoid replaced the Lower Paleozoic carbonates in some areas;
6. Jasperoid stratigraphically takes place of the Leadville Limestone in the drape fold;
7. Except in the collapse area, jasperoid developed in several fracture and quartz filling stages;
8. The Deadman Gulch jasperoid needs to be studied further for thorough understanding of its relationship to the thrust/reverse fault.

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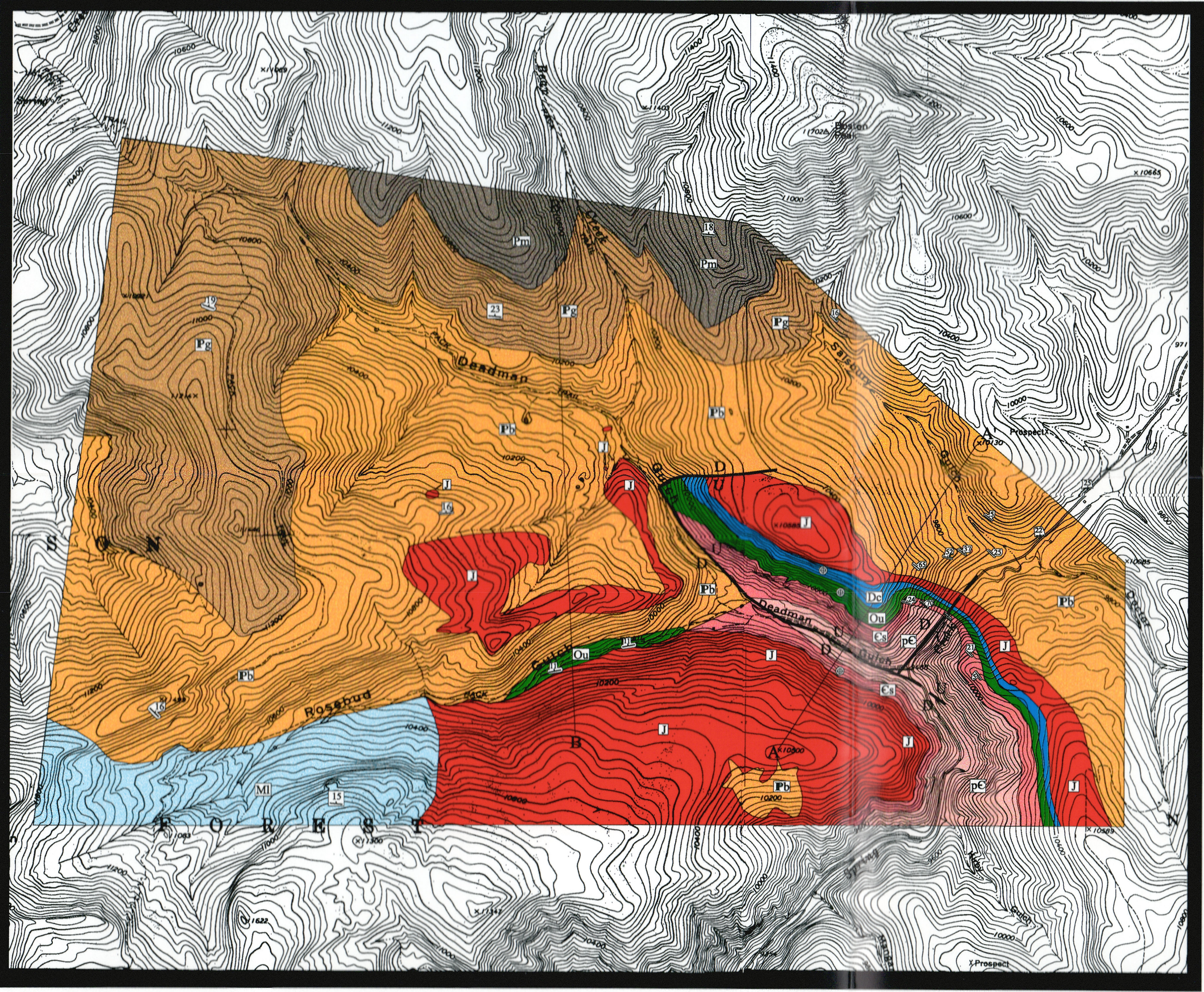
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Geologic Map of Deadman Gulch and the Surrounding Area:
Gunnison County, Colorado

PLATE 1



Explanation

- | | |
|---|-----------------|
| J Jasperoid: Formed during collapse of solution cavities and subsequent precipitation of quartz | } Cretaceous(?) |
| Pm Maroon Formation: Maroon (color) crossbedded conglomerate and sandstone with siltstone and shale beds | } Permian |
| Pg Gothic Formation: Micaceous and arkosic sandstone grading down to black fissile shale | } Pennsylvanian |
| Pb Belden Shale: Black to yellow-tan, fissile shale with thin, moderately fossiliferous limestone layers | |
| --- DISCONFORMITY --- | |
| Ml Leadville Limestone: Moderately fossiliferous, thin to massively bedded limestone with local breccias, micrites, and dolomicrites | } Mississippian |
| --- DISCONFORMITY --- | |
| Dc Chaffee Formation: Light to dark gray mudstone, shale, sandstone, and sandy dolomite layers | } Devonian |
| --- DISCONFORMITY --- | |
| Ou Ordovician undifferentiated: (Fremont limestone and Manitou dolomite) fossiliferous limestone and thick bedded dolomite, respectively | } Ordovician |
| Es Sawatch Sandstone: Fine- to coarse-grained sandstone and coarse-grained quartzite with scolithus tubes | } Cambrian |
| pC Basement Crystalline rocks: Granite and granodiorite with local pegmatites and quartz muscovite schists | } Proterozoic |

- 22 Strike and dip
- ⊕ Horizontal bedding
- × Vertical bedding
- Fault

