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LARAMIDE AND CENOZOIC STRUCTURAL AND PALEOTOPOGRAPHIC HISTORY OF THE OURAY AREA AND THE NORTHWESTERN FLANK OF THE SAN JUAN MOUNTAINS, COLORADO

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Abstract—Regional structural mapping of the base Dakota (base Cretaceous) surface in the northwestern San Juan Mountains discloses a complex intersection of the San Juan Uplift, faulting of the Paradox Basin, and the southern end of the Uncompahgre Plateau. Uplifted areas are associated with the Ouray and Rico centers of Laramide igneous activity, but not with two other such centers. Pre-Cenozoic rocks subcrop in mappable belts, forming the northwest flank of the San Juan Uplift. A more detailed look at the Ouray area, including some deep well control, shows a structural high related to Laramide igneous activity, and at least three monoclines or kink folds each with about 300 m (1000 feet) of vertical offset, verging outward from the mountain mass. Oddly, the Paleozoic monoclinal fold near Ouray was not reactivated. The base Cenozoic is a paleotopographic surface with over 900 m (3000 ft) of relief regionally and over 360 m (1200 ft) in the Ouray area. A pronounced paleovalley passes east-west through Ouray and helps to form the Amphitheater; it is formed along the Lower Hermosa and Molas subcrop which was probably the least resistant pre-Cenozoic units in the area. This paleovalley may have drained a large 'Imogene Basin,' which extended west to Telluride. A second low area (Cow Creek Basin) to the northeast is separated by a high-standing Gold Hill upland underlain by Dakota Sandstone and Laramide igneous sills. South of Silverton, the pre-Cenozoic surface rises sharply; this may mark the southwestern edge of the San Juan volcanic field banked against a 'Grenadier Upland' formed over the Precambrian and Paleozoic rocks of the Laramide San Juan Uplift.

INTRODUCTION

The western San Juan Mountains of southwestern Colorado are known for their stunning scenery. A complex geologic record from Precambrian to Cenozoic is widely exposed due to intense glacial erosion. Economic resources of gold, silver and other metals have led to detailed exploration and mapping. However, important structural and stratigraphic problems remain in the San Juan Mountains.

The present study focuses on the northwestern part of the western San Juan Mountains, from Rico to Ridgway, and Silverton to Placerville, centered on the cities of Ouray and Telluride (Fig. 1). The regional maps presented include all of Ouray and San Juan counties and parts of San Miguel, Dolores, Montrose and Gunnison counties. This area has extensive exposures of Mesozoic rocks beneath Cenozoic cover, and limited exposure of Paleozoic and Precambrian strata. The geologic history can be briefly summarized as follows (see Blair, 1996 for more detailed description).

The Precambrian, now exposed in the Uncompahgre Gorge south of Ouray, consists of tightly folded quartzite and argillite overlain by thin Devonian and Mississippian marine shelf strata. In the Late Paleozoic, the area formed the southeastern end of the Paradox Basin, with marine and marginal-marine Hermosa Group sediments overlain by Cutler nonmarine redbeds. The area includes the southern faulted margin of the Uncompahgre Uplift, as well as a distinctive kink fold and high-angle fault of Paleozoic age in and near Ouray townsite. Mesozoic rocks were deposited on folded Paleozoic strata, consisting of

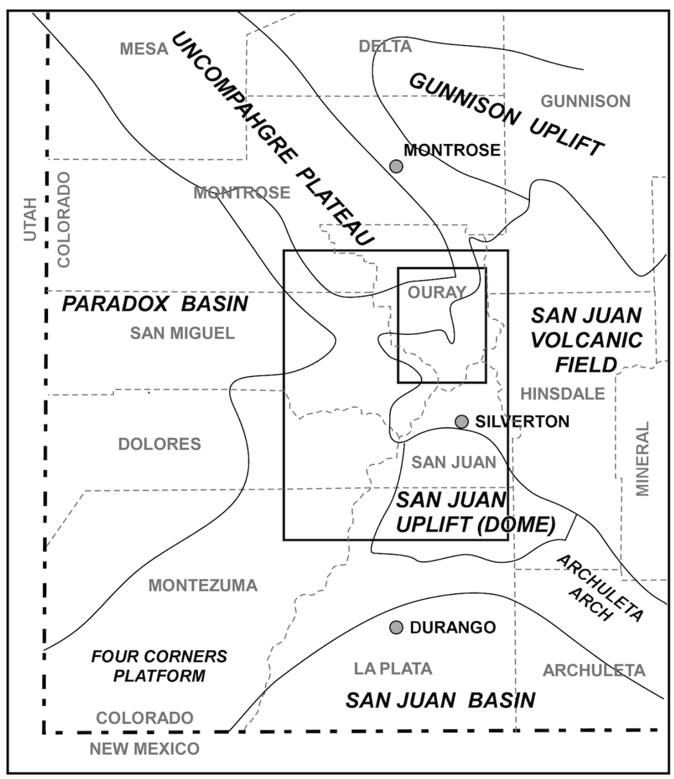

FIGURE 1. Location of the study area (larger box, regional area; smaller box, Ouray area), and its relationship to structural features in southwestern Colorado.

nonmarine Triassic and Jurassic rocks (Dolores, Entrada, Wanakah and Morrison), the regional fluvial to marginal-marine Dakota Sandstone of mid-Cretaceous age and the overlying marine Mancos Shale.

Laramide tectonism (post-Mancos, pre-San Juan volcanics) includes both structural deformation and igneous activity (see Dickinson et al., 1968). The Mesozoic rocks were faulted and generally tilted northwesterly from the crest of the San Juan Uplift. This uplift may have begun as early as late Campanian (Cather, 2004). Mesozoic strata were stripped off of the core of the uplift; they subcrop beneath Cenozoic rocks in a band across the study area. Igneous activity that forms part of the Colorado Mineral Belt includes a stock, sills and dikes in the Gold Hill area north of Ouray (Uncompahgre mining district), intrusive rocks in the Cow Creek area northeast of Ouray, and two centers near Rico. Latest Cretaceous volcanic rocks are preserved in a basin at the northeast corner of the study area (Cimarron Ridge Formation; Dickinson et al., 1968).

The Laramide San Juan Mountains were deeply eroded before the deposition of Cenozoic rocks. The pre-Cenozoic (pre-Paleogene or pre-Oligocene) surface is one of high relief, and a subject of this paper. In some areas, the surface is overlain by a nonvolcanic Telluride Conglomerate (thickest to the west and south); both the Telluride and the older surface are overlain by over 600 m (2000 ft) of volcaniclastic rocks with minor andesitic lavas of the San Juan Formation. Subsequent volcanic activity formed a series of flat-lying ash-flow tuff sheets prominent between Ouray and Telluride, as well as major fault-bounded cauldron subsidence structures such as the Silverton Cauldron.

This paper takes a regional view of the Laramide structural development and the pre-Cenozoic topography of the northwestern San Juan Mountains, as well as a closer look at features in the Ouray area.

METHODS USED

The San Juan Mountains and Paradox Basin have been mapped at various scales, primarily by geologists of the U.S. Geological Survey. Regional maps at 1:250,000 or 1:100,000 include the Montrose 0.5°x1° (Steven and Hall, 1989), Durango 1°x2° (Steven et al, 1974), Moab 1°x2° (Williams, 1964) and Cortez 1°x2° (Haynes et al., 1972). About 50% of the study area is mapped by published geologic quadrangles at 1:24,000 scale (see list in Appendix). Weimer (1981) also completed detailed mapping in the Ridgway area.

A map base was compiled from published maps. On this map, the base of Dakota (base Cretaceous, top Morrison) and the base of Cenozoic were identified and elevations picked from contouring on 1:24,000 maps. The base Dakota picks were extended in the Ouray area by using picks on the base of Entrada, which generally lies about 900 ft (280 m) below the main horizon, as seen in surface outcrops near Ouray and Telluride. Base Dakota is preferred to top Dakota for use as a mapping horizon, as the Dakota is a bench former; its base lies on steep slopes and can be reliably mapped. Structure on the base Dakota level represents the sum of Laramide and later tectonic activity in the area. The base of Cenozoic occurs either at the base of the San Juan Formation (andesitic breccia and volcaniclastic rocks) or the underlying Telluride Conglomerate (nonvolcanic conglomerate, thickest near Telluride and Ophir). Subsurface data from a few wells in Ouray County were added to extend the contouring in the Ridgway area. Since the well and surface data are presented in feet above sea level, the maps are contoured in feet.

The southeastern pinchouts of Mesozoic and Paleozoic units beneath Cenozoic cover were identified where they are exposed, and then connected using available map data and geologic judgment.

REGIONAL STRUCTURE ON BASE CRETACEOUS (BASE DAKOTA)

The regional structure on the base of Cretaceous is depicted on Figure 2, along with the zones where Mesozoic and older units subcrop below the base of the Cenozoic. The San Juan Uplift is clearly shown on the east side of the map by the subcrop of Precambrian below Cenozoic cover in San Miguel and Ouray counties. Northwest dips away from the uplift are fairly steep; the Base Cretaceous horizon drops 1000-1400 ft (300-420 m) in a span of 2-5 miles (3-8 km) from its elevation where it subcrops. Within this area are several unusual monoclines, which will be discussed in a later section.

To the west and northwest are a complex of faults and low-relief domal structures that represent the southeast end of the Paradox Basin of late Paleozoic age. Important highs in this area are the Placerville horst and anticline northwest of Telluride and the Dallas high to the northeast. Faults are abundant; major northwest-trending faults include the Black King fault near Placerville and the Vanadium fault, which extends into the Telluride area. These features may result from Laramide compression acting on the Mesozoic and Permian rocks that overlie a mobile Pennsylvanian evaporite layer (Paradox Salt) at depth.

To the north, the east-west Ridgway fault bounds a large, gently northeast-dipping block, which is the southeastern end of the Uncompahgre Plateau. This dip continues northeastward into a significant basin that preserves Fruitland strata (latest Cretaceous) and latest Cretaceous volcaniclastic strata of the Cimarron Ridge Formation (Dickinson et al., 1968). The basin continues north, abutting the Gunnison Uplift along the Cimarron fault. Not finding a better name, I'm terming this the 'Storm King Basin'. Both the plateau and the basin are located in the area of the late Paleozoic Uncompahgre Uplift (Weimer, 1980). Limited wells and outcrops show Triassic and Jurassic rocks overlying Precambrian.

To the southwest in Dolores and Montezuma counties, the flank of the San Juan Uplift extends west and broadens into a gently dipping homocline that outlines the Rico Dome and continues south towards Cortez. The pre-Cenozoic subcrop of Dakota and older strata is not determined in the southern part of the area due to subsequent erosion (or nondeposition) of overlying Cenozoic rocks.

Four centers of Laramide igneous activity lie along a northeast-trending line that crosses the region. (Additional centers

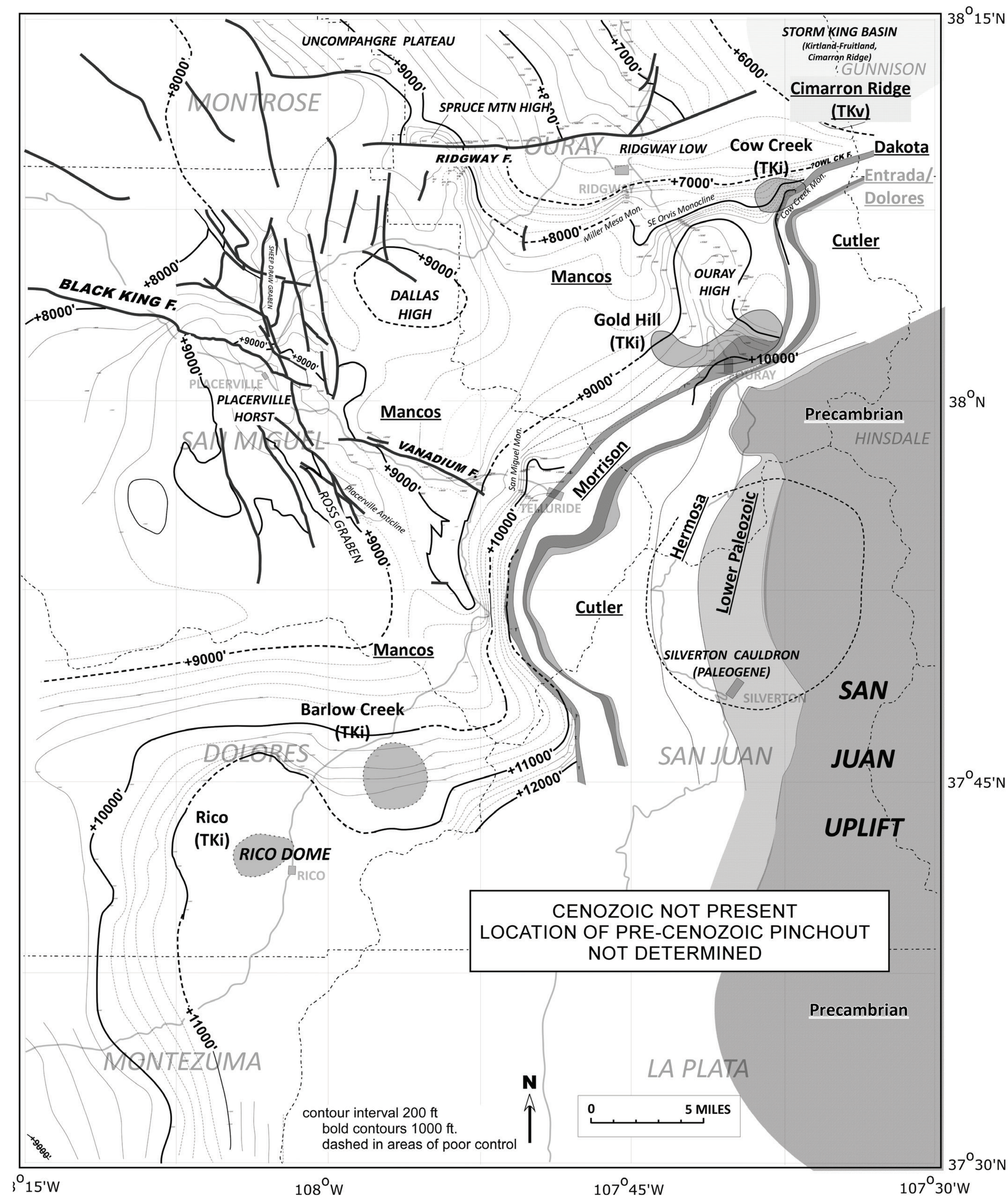

FIGURE 2. Regional structure map on base of the Dakota Sandstone (base of Cretaceous), also showing the subcrop of Dakota and older strata beneath the Cenozoic volcanic and sedimentary cover, and the location of Laramide igneous centers.

may exist in the northeastern part of the area but be hidden beneath Cenozoic cover.) Two of these centers, the Gold Hill center at Ouray and the Rico center at Rico, are associated with significant to large domal uplift and are also significant mining districts. Two others, Barlow Creek and Cow Creek, have no associated uplift and (coincidentally?) do not host significant mining districts.

REGIONAL PALEOTOPOGRAPHY ON BASE OF CENOZOIC

Using the same regional map base, the elevation of the base of the Cenozoic (San Juan volcanics and Telluride Conglomerate) is shown on Figure 3. The surface generally occurs at elevations of 9000 to 13,000 ft (2700-4000 m), except within the Silverton Cauldron, where it has sunk to unknown depths. The surface shows up to 1200 ft (370 m) of relief within local areas, as well as larger-scale features. There is no obvious structural doming associated with the Silverton and other cauldrons.

South of Silverton and Ophir, the surface rises to over 13,000 ft (4000 m) and is lost. Mountains to the south (Grenadier and Needles ranges) reach greater than14,000 ft (4270 m) in altitude. This area, called here the 'Grenadier Upland,' may have formed the original southern limit of the San Juan volcanics in the western San Juan Mountains, as no erosional remnants of volcanic rocks are found in the shaded area or to the southwest.

North of this highland, the surface slopes gently to the north and northeast in the Ophir-Telluride area. Paleoridges and paleovalleys can be defined in the Ophir area and also in the Last Dollar area northwest of Telluride. At Telluride itself, the surface slopes to the east, dropping below 10,000 ft (3050 m) elevation. When next seen near Ouray, the surface appears as a high-relief paleovalley that passes through Ouray and the Amphitheater just southeast of Ouray. These two occurrences suggest an 'Imogene Basin' that serves as a catchment area for the Amphitheater paleovalley. Just to the north of the paleovalley, a high area is underlain by the sills of the Gold Hill igneous center and resistant Dakota Sandstone. Farther northeast, a low basin (below 9,000 ft, 2,740 m elevation) seems to drop eastward towards Cow Creek. The surface rises to the north to the 'Silver Jack Upland'. Just south of Silverton, the surface dips steeply north, tracing the southern erosional wall of the Silverton Cauldron.

This surface is best interpreted as buried topography. The prevolcanic drainage appears to flow to the north and northeast, into an area now entirely concealed by San Juan volcanics. This suggests some sort of drainage divide to the southwest and south, probably within the Grenadier Highlands, separating the study area from the Eocene rocks of the San Juan Basin (see Cather, 2004).

In many places, the pre-Cenozoic surface is overlain directly by the andesitic breccias and volcaniclastic rocks of the San Juan Formation. In other places, a nonvolcanic Telluride Conglomerate caps the surface. The Telluride is generally thicker to the west in the Telluride-Ophir area, and surprisingly little is found in the Amphitheater paleovalley area. The Telluride may represent some sort of gravel fan shed from the Grenadier Upland that is restricted to the headwaters area.

POST-DAKOTA STRUCTURAL FEATURES IN THE OURAY AREA, AND THE PROBLEM OF THE MONOCLINES

A closer focus on the Ouray area (Telluride to Ridgway) is warranted because of the excellent exposure of distinctive and interesting geologic features, as well as being the site of the 2017 New Mexico Geological Society field conference. The contour map on base of Cretaceous (base Dakota), combined with the subcrop belts of Dakota and older strata, is shown on Figure 4.

The subcrops of Mesozoic strata show a steady northeast trend, which turns northerly, then easterly in the Cow Creek area. The Precambrian subcrop has a pronounced nose south of Ouray, which has two causes. The subcrop pattern is partly governed by the very resistant Uncompahgre Group quartzites in this area that elevate the base Cenozoic surface. But the pattern also represents Paleozoic uplift at and south of the Ouray fault (the "Sneffels horst" of Baars and See, 1968). The Cutler subcrop vanishes near Ouray due to pre-Triassic uplift and truncation, as seen in the valley near Ouray.

At the north end of the Ouray area is the Uncompahgre Plateau and the east-west striking Ridgway fault. The dip angle of this fault is unknown, but it is mapped as high-angle where it is exposed offsetting Morrison against Mancos. The fault apparently marks the southern boundary of the Uncompahgre Uplift of Late Paleozoic age; three deep wells south of the fault in the Ridgway Low penetrate a Paleozoic section similar to that at Ouray. The present fault is a Laramide reactivation of the Paleozoic fault, but we don't know the kinematics of either event.

South of the Ridgway Low (conspicuous to the traveller by its badland hills of Mancos mudstones), the base Cretaceous surface rises towards the San Juan Uplift. In the Ouray area, a conspicuous dome is established, here called the 'Ouray High'. The high reaches a gentle peak then is essentially flat to the area near Ouray townsite, where it rises again south-southeastward to the Dakota pinchout. The dome may be associated with the Gold Hill igneous center of Laramide age, which includes a stock at Skyrocket Creek, numerous sills that intrude the sedimentary sequence, and abundant dikes and veins. The apex of the high lies near the deep Ouray valley, such that strata dip away from the valley on either side as marked by Luedke and Burbank (1962, also see Burbank and Luedke, 2008). It's possible that this has an element of a 'valley anticline' formed by uplift due to local erosion of sediment over a ductile substrate. However, we don't have a known ductile substrate in this area unless it is present in the lower Hermosa Group. Also there is no evidence for valley anticline development in the Telluride glacial valley (southwest part of Fig. 4), which is almost as deep.

The most distinctive feature of the base Cretaceous surface is the presence of four monoclinal folds. The San Miguel monocline lies just west of Telluride; it trends nearly north-south, dips to the west 22-25°, and shows 800-1000 ft (240-300 m) of vertical relief. To the north, three monoclines dip northwesterly and are arranged in en echelon fashion. The

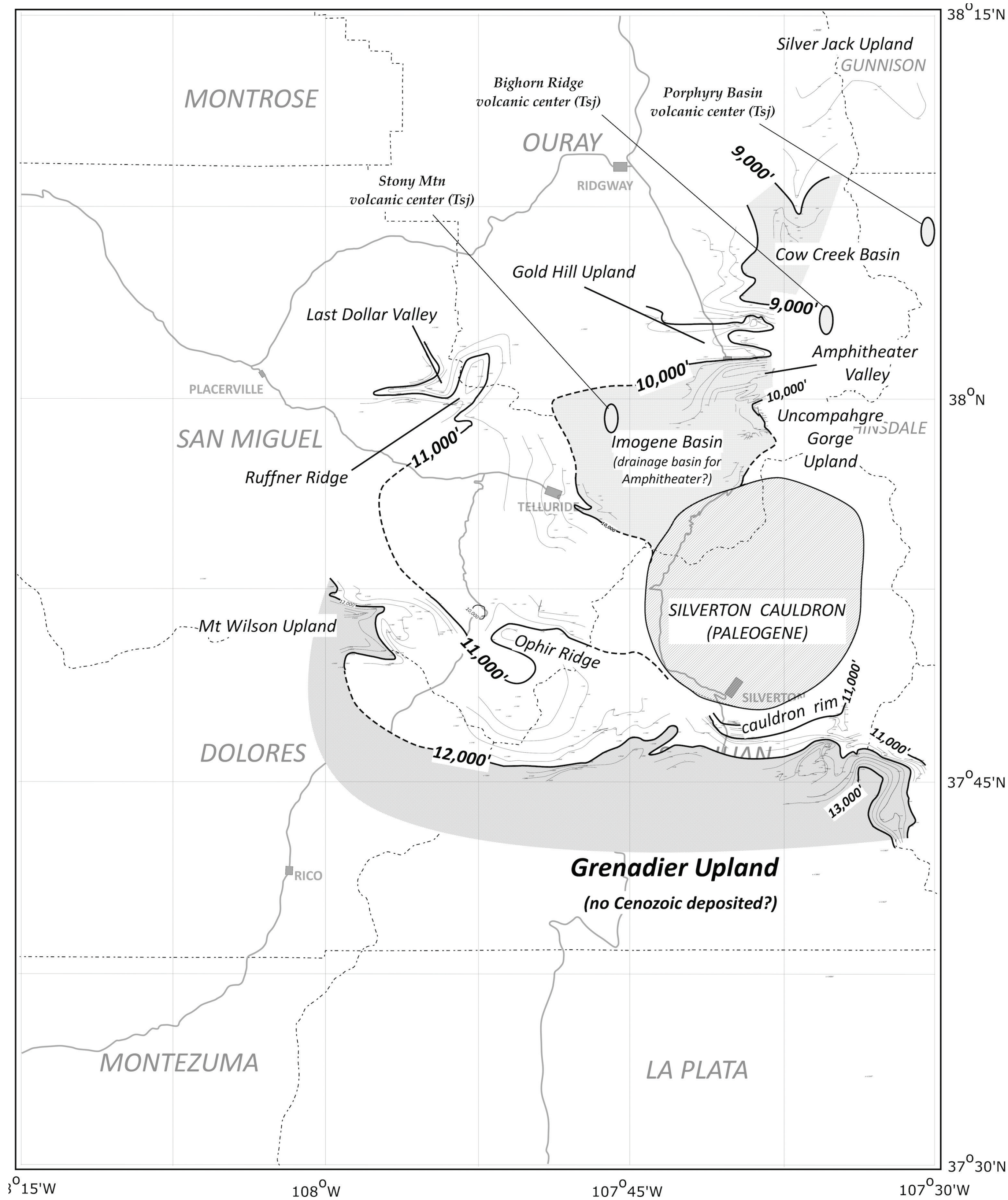

FIGURE 3. Regional contour map of the base Cenozoic erosion surface.

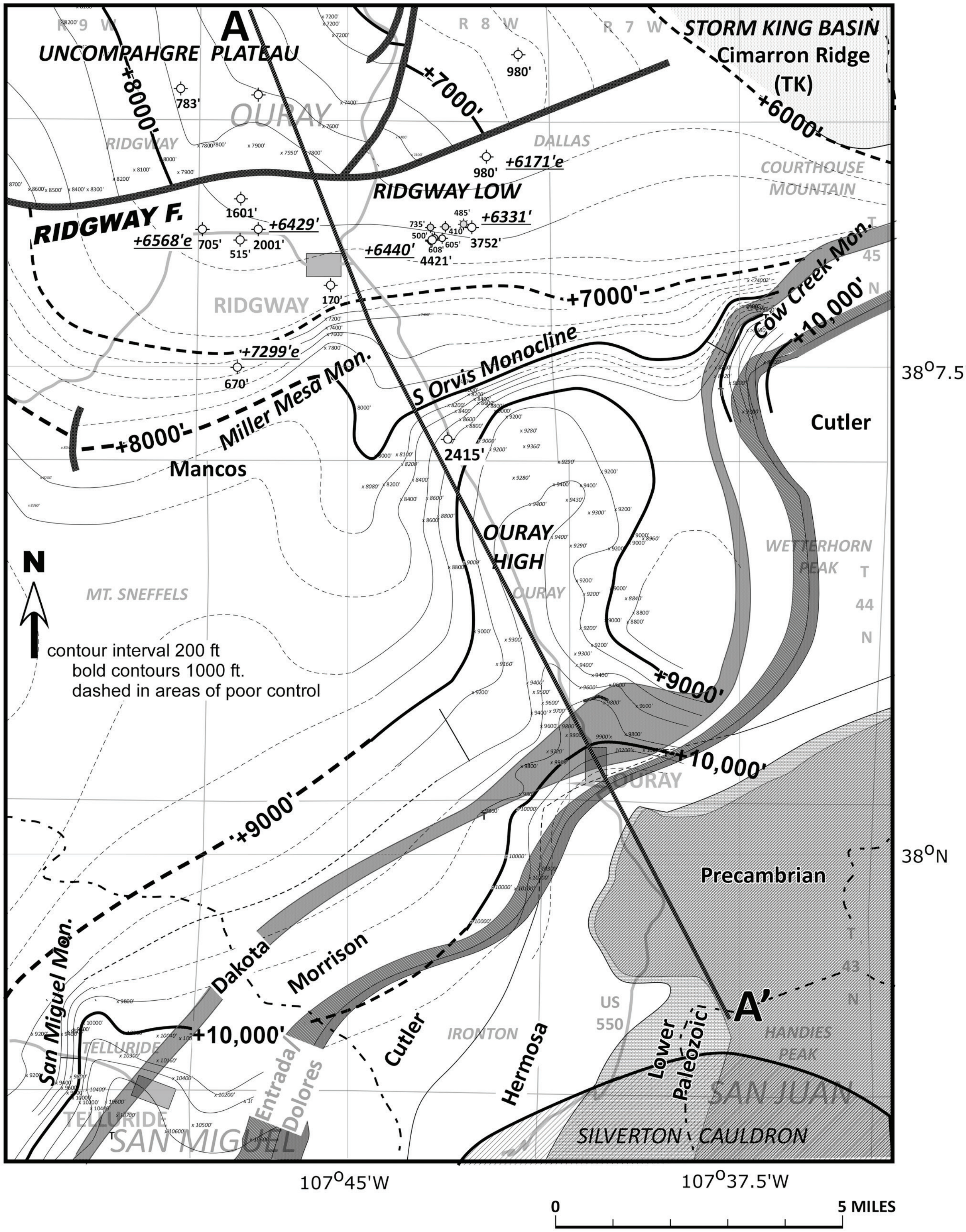

FIGURE 4. Ouray area: Structure map on the base of the Dakota Sandstone (base of Cretaceous), also showing the subcrop of Dakota and older strata beneath the Cenozoic cover. Base shows names of 7.5’ quadrangles and township boundaries. Available well control near Ridgway is shown, with numbers in italics indicating elevation of the base of the Dakota Sandstone (top of Morrison Formation).

Miller Mesa monocline is exposed south of Ridgway (Fig. 5); it strikes N55°E, dips 20° to the NW, and shows 1000 ft (300 m) of vertical relief. To its southeast, the Orvis South monocline strikes N52°E, dips 20° to the NW, and shows 1000 ft (300 m) of vertical relief. To the east in the Cow Creek valley, the Cow Creek monocline strikes N30°E, dips 24-35° to the northwest, and has over 1500 ft (460 m) of vertical relief.

As is evident from these data, the monoclines are closely similar in vertical relief and dip angle. All of them indicate compressional movement to the west and north, away from the center of the San Juan Uplift. In form they are kink folds with parallel axial planes and a consistent tilted panel between them. Their vergence is to the west (San Miguel, Cow Creek) or northwest (Mitchell Mesa, Orvis South). They represent small amounts of shortening; a calculation on the San Miguel monocline shows about 194 ft (59 m) of shortening across the fold, or a shortening of about 8%.

The Intex #1 Halls was drilled on the upthrown side of the Orvis South monocline. From the well records at the COGIS website (cogcc.state.co.us/cogis), the well penetrated the Hermosa Group and continued into the lower Hermosa, where it penetrated and reached total depth in a quartz latite intrusive (sill?) greater than 65 ft (20 m) thick. The intrusive is probably a sill within the weak Lower Hermosa and Molas mudstone section but it reached a point over 4 miles (6 km) north of the igneous center. Inflation of a sill in the Lower Hermosa might explain the Orvis South monocline, possibly enhanced by northwest creep of the overlying sediments over the sill or the Molas shales. However, no evidence exists for Laramide igneous rocks anywhere near the San Miguel monocline, nor near the Miller Mesa monocline.

The monoclines could be seen as Laramide tectonic features, indicating deeper faulting. The en echelon Miller Mesa and Orvis South monoclines may overlie the deeper 'Orvis fault' of Paleozoic age postulated by Weimer (1981), and could represent slight strike-slip reactivation of that feature. But why should this style have been preferred here when it is not observed elsewhere in the Paradox Basin? Also, wouldn't Laramide folding have reactivated the Paleozoic Ouray fault and fold - a fold of similar characteristics?

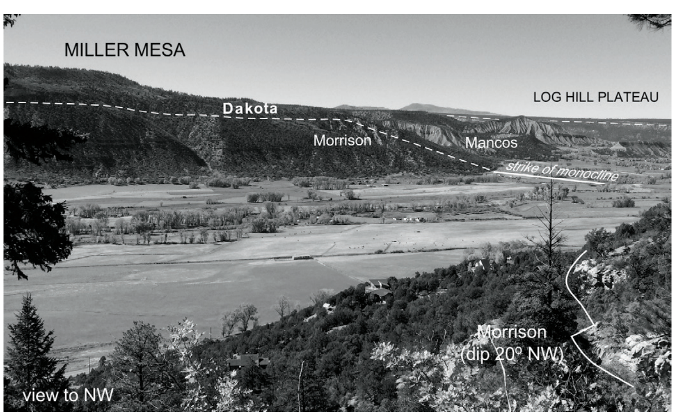

FIGURE 5. View to northwest from trail up Orvis South monocline, showing Miller Mesa monocline and Mancos badlands to its north; Log Hill Plateau on north side of Ridgway fault in the right distance. The contact of Dakota and Morrison strata is dashed.

My favored explanation at this point is one of gravitational gliding; outward and downward translation of the Paleozoic and Mesozoic sedimentary package away from the crest of the San Juan Uplift, riding above the weak decollement zone of the Lower Hermosa and Molas formations. Dip rates off of the dome are generally only 200-600 ft/mile (38-114 m/km, or 2.2°- 6.5° dip) but total vertical drop exceeds 4,000 ft (1,200 m). The geometry of the kink folds were probably determined by the thickness of the sedimentary column and the limited amount of translation. Their location may be influenced by deeper Paleozoic structures, as suggested by Weimer (1981).

BASE OF CENOZOIC TOPOGRAPHY IN THE OURAY AREA

Figure 6 shows the base of Cenozoic topography in the same Ouray map area. There are two low areas; the Imogene Basin to the southwest of Ouray and the Cow Creek Basin to the northeast, separated by an upland that underlies Gold Hill and nearby mountains. To the southeast of Ouray is the Uncompahgre Gorge highland.

The Imogene Basin is defined by the steady eastward dips of the surface in the Telluride area, and the lower elevations in Canyon Creek southwest of Ouray . Southeast of Ouray is the Amphitheater which hosts a spectacular exposure of a prevolcanic paleovalley of about 1000 ft (300 m) relief (Fig. 7). The Amphitheater Paleovalley overlies the subcrop of the nonresistant, shale-rich Lower Hermosa and Molas formations. The paleovalley is easily visible by looking eastward into the Amphitheater from the Box Canyon bridge or from the overlook. To the southwest, the paleovalley seems to pass under volcanic rocks of Hayden Mountain at a low angle on the south side of Canyon Creek.

The Quaternary history of the Ouray area including the excavation of the Amphitheater along the old pre-Cenozoic paleovalley, remains to be studied in detail. I suspect that the Amphitheater originally formed by slumping of the volcanic rocks on the weak Lower Hermosa and Molas sediments once the deep Ouray glacial valley was formed. Subsequent glacial advances, combined with rockfalls and debris flows, have emplaced a deep cover of till and debris that floor the Amphitheater today.

North of the paleovalley, the Gold Hill upland is underlain both by resistant Dakota Sandstone and by a thick sill intruded into the immediately overlying Mancos shale. South of the paleovalley, the Uncompahgre Gorge upland is underlain by the steeply-dipping and highly resistant Uncompahgre Group quartzites of Proterozoic age. The high and irregular topography is easily seen by passengers in cars driving up the gorge south of Ouray.

Two igneous centers of the Paleogene San Juan Formation occur in the area, as defined by stocks and radiating dike swarms. Neither the Bighorn Ridge center nor the Stony Mountain center (on the road to Yankee Boy Basin) show any association with the prevolcanic topographic anomalies.

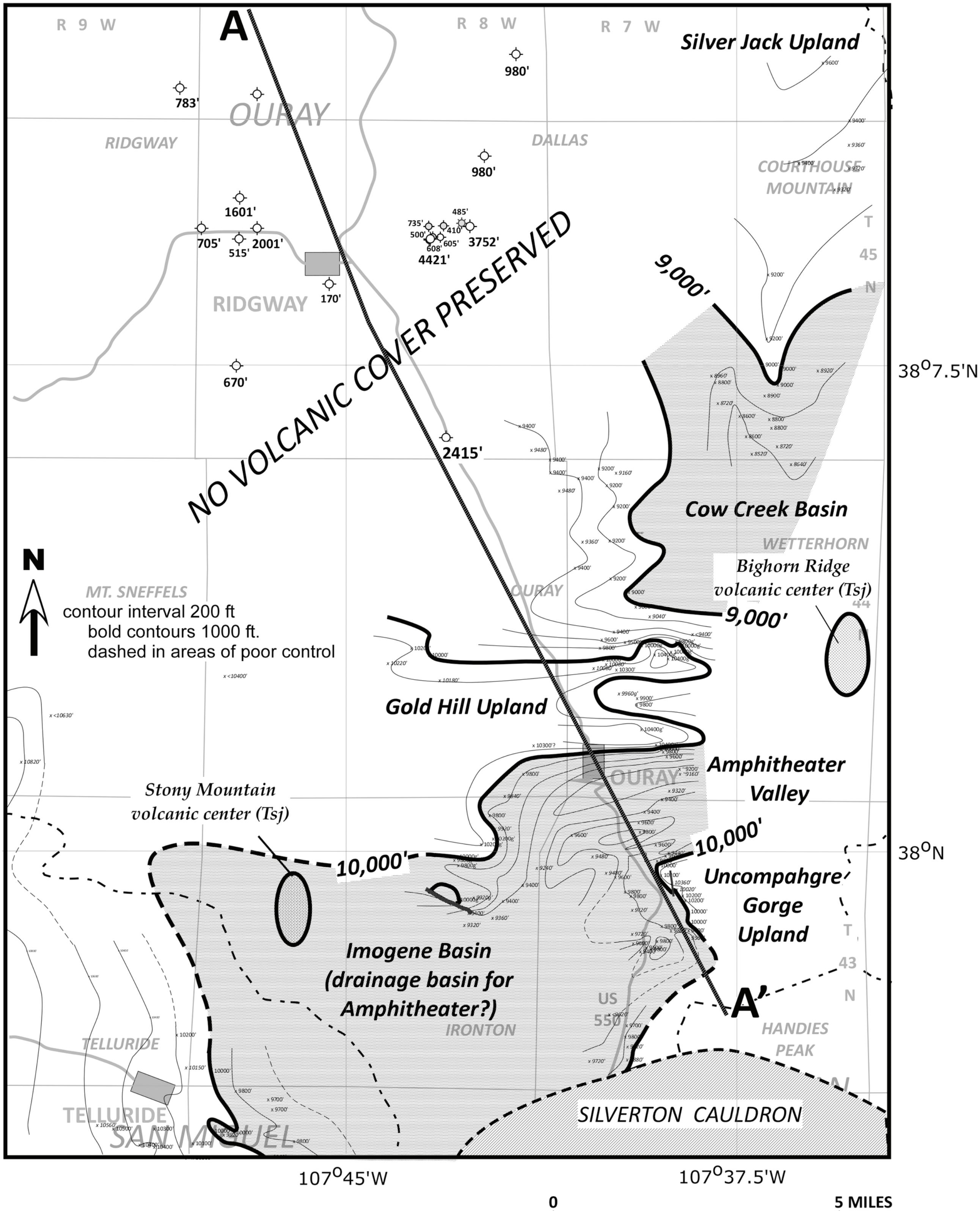

FIGURE 6. Ouray area: Detailed contour map of the base Cenozoic erosion surface. Centers of San Juan Formation igneous activity are shown.

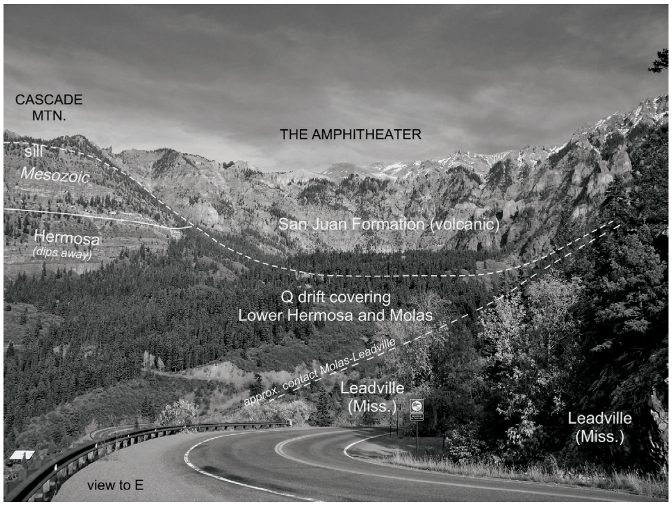

FIGURE 7. View of the Amphitheater from the Ouray overlook on US 550; outline of Amphitheater paleovalley on pre-Cenozoic erosion surface is marked.

SUMMARY AND FURTHER WORK

The major relationships seen in the Ouray area are summarized in the cross-section of Figure 8. The high mountains are underlain by San Juan volcanics, which lie on older rocks with a substantial buried topography. The older rocks dip gently north and northwest, more steeply to the southeast near the pinchout of Paleozoic and Mesozoic rocks. The section shows the Orvis South monocline and also the northeast tail of the Miller Mesa monocline; both of them could be associated with a deeper Paleozoic basement-involved fault, which could control the location of Orvis Hot Springs as suggested by Weimer (1981). To the north is the Ridgway fault, separating the Paleozoic stratigraphy of Ouray from the late Paleozoic Uncompahgre Uplift. This fault was reactivated locally in the Laramide (probably), but other Paleozoic features including the Ouray fault and fold were not reactivated.

Despite the considerable amount of work done on this area, there is opportunity for much more geological research. It would be of interest to look at fracture and fault orientations around the monoclines to see if the kink fold model is appropriate. Similar studies along the Ridgway fault might help to establish its sense of motion in the Laramide. Geophysical studies would help to determine the dip and kinematics of the Ridgway fault and the monoclines. A better stratigraphic understanding of the Lower Hermosa and Molas units, poorly exposed northeast of Box Canyon in Ouray, would give more information on their potential mobility. The remote but interesting Cow Creek area needs to be fully mapped.

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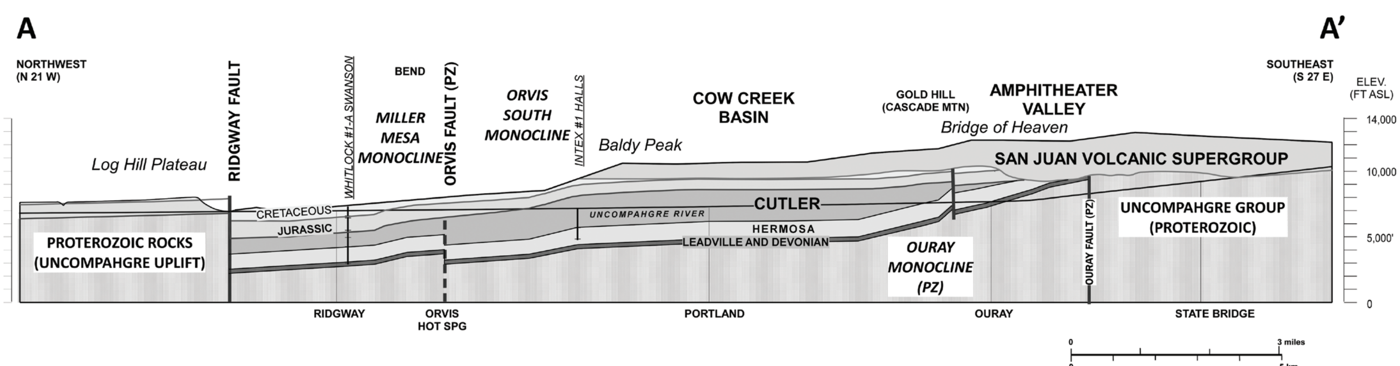

FIGURE 8. Cross section of the lower Uncompahgre Valley, Ridgway to Ouray and Poughkeepsie Gulch. Line of section is shown on Figure 4.

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APPENDIX: GEOLOGIC QUADRANGLE MAPS USED IN THE REGIONAL MAP.

Horsefly Peak:	Hall, 1988	MF 2059
Ridgway:	Hall, 1989	MF 2100
Courthouse Mountain:	Dickinson, 1988	GQ 1644
Placerville:	Bush et al., 1959	Bulletin 1072-E
Ouray:	Luedke and Burbank, 1962	GQ 152
Wetterhorn Peak:	Luedke, 1972	GQ 1011
Little Cone:	Bush et al., 1960	Bulletin 1082-G
Gray Head:	Bush et al., 1961	MF-1766
Telluride:	Burbank and Luedke, 1966	GQ 504
Ironton:	Burbank and Luedke, 1964	GQ 291
Handies Peak:	Luedke and Burbank, 1987	GQ 1595
Dolores Peak:	Bush and Bromfield, 1966	GQ 536
Mount Wilson:	Bromfield, 1967	Bulletin 1227
Ophir:	Luedke, 1996	GQ 1760
Silverton, Howardsville:	Luedke and Burbank, 2000	I-2681
Rico:	Pratt et al., 1969	GQ 797