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Part 1

Physical Environment of the San Juan Mountains

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A Legacy of Mountains Past and Present in the San Juan Region

David A. Gonzales and Karl E. Karlstrom

THROUGHOUT TIME, PEOPLE HAVE BEEN DRAWN TO MOUNTAINS for inspiration, recreation, and scientific exploration. Mountains are also vast warehouses of natural resources and libraries of geologic history.

Mountains form in response to the dynamic forces of our planet. The life spans of mountain belts, from initial uplifts to erosion to base levels, run from tens of millions to hundreds of millions of years. Ancient and active mountain belts are part of the fabric of continental crust and provide clues to events that build and reshape continents. The concept of plate tectonics (Condie 1989) provides a framework within which to investigate and explain mountain building. (For a summary of plate tectonics, refer to *The Western San Juan Mountains*, chapter 2.)

The San Juan Mountains are part of the extensive Southern Rocky Mountains (figure 1.1) and are dominated by some of the highest and most jagged summits in the continental United States. The San Juans reveal a fascinating geologic story of the creation and demise of many mountain ranges in this region during the past 1.8 billion years, including probable current uplift from active mountain-building processes.

The history of any mountain belt is deciphered from its modern landscape and the remaining rock record. An understanding of the geologic evolution of the San Juan Mountains comes from many studies done over the past 125 years. Field

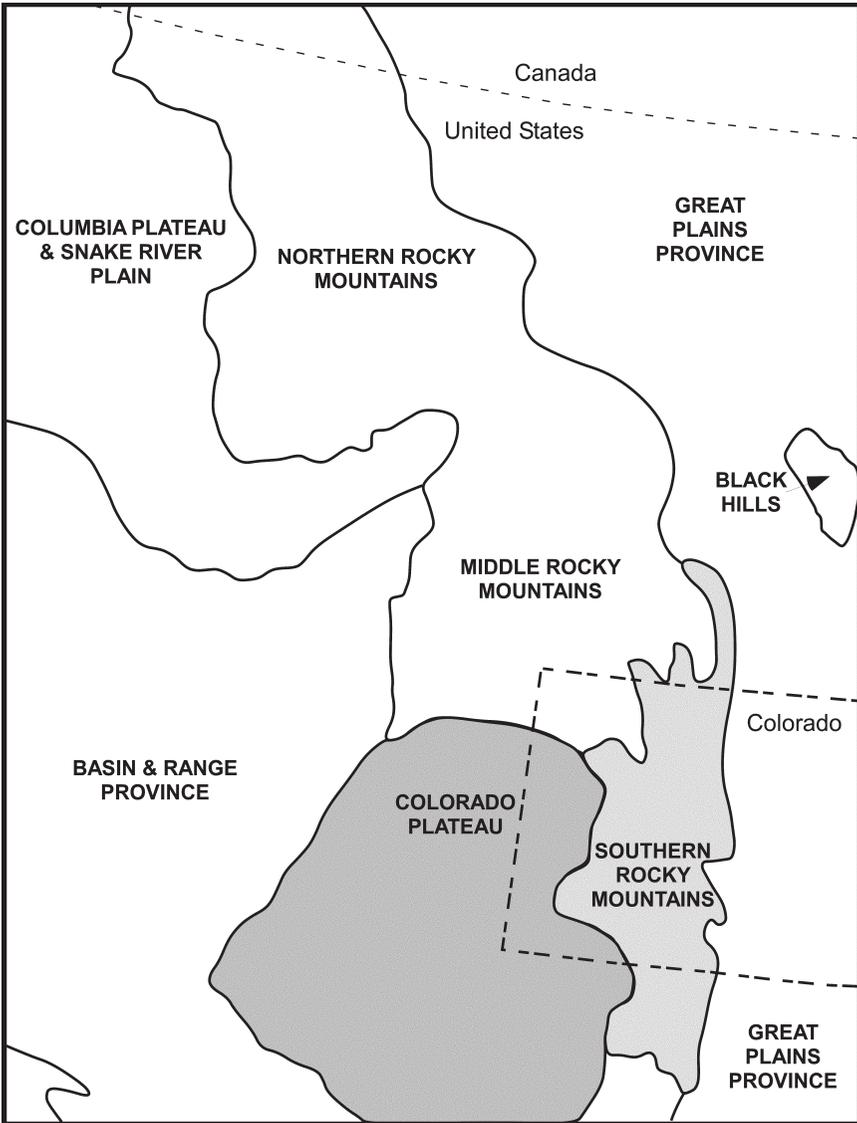


FIGURE 1.1 Physiographic provinces of the Four Corners region showing the extent of the Colorado Plateau and the Southern Rocky Mountains. From <http://www2.nature.nps.gov/GEOLOGY/usgsnps/province/INDEXrockyMtnSUBS.gif>.

studies of rocks exposed in the region are supported by satellite images, geophysical probes of the deep earth, measurements of rock ages, and analyses of rock compositions. These data give geologists the ability to reconstruct the geologic history in

the San Juan Mountains over a span of nearly two billion years, almost half the age of the Earth.

The modern San Juan Mountains preserve a history of many geologic events. In this chapter, we provide a basic overview of our understanding of these events within the context of models geologists have proposed.

ASSEMBLY OF A CONTINENT

Evidence of the oldest mountain-building events in the San Juan Mountains is preserved in ancient rocks that are exposed mostly in the Needle Mountains, along the southwestern edge of the San Juan Volcanic Field (plate 1), and on some of the area's isolated peaks and in some of its deeply eroded canyons. The Precambrian rocks in the San Juan Mountains were formed during ancient mountain-building events, between 1.8 and 1.0 billion years ago (Ga). Long ago, these rocks were eroded and beveled to sea level, leaving only their contorted mid-crustal roots to be studied. In the discussion that follows, we use the present location of North America as a reference point, although the continents have shifted positions over time and North America's old rocks did not form at the latitudes and longitudes at which they are now exposed.

The continental crust that forms the foundation of the San Juan Mountains was assembled in a series of continent-scale interactions along the previous edge of North America, during the early to middle Proterozoic (plate 2). Formation of these oldest mountains involved landmass collisions accompanied by magmatism and widespread contortion of rocks. This hypothesized scenario is similar to the tectonic processes active in modern Indonesia. In Indonesia, the Australian plate, which is analogous to the continental nucleus of proto-North America, is colliding with numerous volcanic-arc terranes (e.g., New Guinea and Sumatra), all of which are being sutured together to form a larger continental mass.

It is hypothesized that prior to 1.8 Ga, an ancient landmass known as Laurentia had been assembled by the accretion of rocks older than 2.5 Ga in a series of regional tectonic events (Van Schmus et al. 1993) (plate 2). The margin of this landmass was located along the present-day Colorado-Wyoming border. A volume of evidence indicates that between 1.8 and 1.7 Ga, large tracts of new continental crust were generated in subduction zones on or near the edge of Laurentia. This new crust collided with and was added to the margin of Laurentia in one or more regional tectonic events, forming the crustal foundation of Colorado and the Four Corners region (plate 2) (Gonzales and Van Schmus 2007; Karlstrom et al. 2004; Whitmeyer and Karlstrom 2007).

An alternative hypothesis to explain the creation of ancient crust in Colorado has been proposed in the past ten years (Bickford and Hill 2006; Hill and Bickford 2001). In this model, the edge of Laurentia, consisting mostly of rocks that are now ~1.85 Ga, extended into what is now central Colorado. This margin of Laurentia

then underwent extensive rifting and magmatism between 1.8 and 1.7 Ga, producing large volumes of mafic-to-felsic volcanic and plutonic rocks. The key point in this model is that the edge of Laurentia was recycled and modified by later tectonic and magmatic events rather than composed of new additions of Proterozoic magmatic-arc crust.

In the Needle Mountains of southwestern Colorado (plate 2), the Irving Formation and Twilight Gneiss are interpreted as the remnants of ancient amalgamated oceanic volcanic-arc mountains that formed between 1.8 and 1.75 Ga (Barker 1969; Gonzales 1997; Gonzales and Van Schmus 2007). This block of crust was added to Laurentia between 1.73 and 1.7 Ga in a regional tectonic event known as the Yavapai orogeny (Karlstrom et al. 2004) (plate 2).

Following erosion and beveling of ancient volcanic-arc mountains in what is now southwestern Colorado, the region was covered by marine and river deposits sometime after 1.69 Ga. Deposited in tectonic basins that developed during continued regional convergence and compression (Karlstrom et al. 2004), these rocks were later buried during thrusting events and metamorphosed.

The period between 1.4 and 1.0 Ga was marked by episodes of magma generation over the present-day region of the San Juan Mountains. These events involved the emplacement of large masses of mostly granitic magma beneath the margin of Laurentia and were possibly related to renewed convergent tectonic events (subduction or continent collision). The granitic rocks formed during these events have been eroded into some of the majestic and rugged peaks in the Needle Mountains, such as the 14,000-foot Eolus, Sunlight, and Windom Peaks.

Regionally, tectonic events between 1.8 and 1.0 Ga in the San Juan Mountain region (plate 2) generated and modified crustal provinces over an extended period (Gonzales 1997; Gonzales and Van Schmus 2007). Mountain building during this period was a product of the assembly of crustal blocks along the entire edge of Laurentia. These events are collectively responsible for the formation of the crust beneath Colorado and are evident only in the vestiges of the now-eroded Precambrian mountain belts. The crustal-scale fabrics (i.e., faults, folds, and weak zones) created in these ancient mountain-building events, however, appear to have had important controls on the location and formation of many younger events, such as magmatism and mineralization along the Colorado Mineral Belt (Karlstrom et al. 2005; McCoy et al. 2005a).

THE ANCESTRAL ROCKY MOUNTAINS

Geologists have established many lines of evidence to indicate that, starting about 300 Ma, all of the world's major landmasses were assembled into a supercontinent called Pangaea (plate 3). Formation of this supercontinent is hypothesized as a series of major plate collisions that occurred between two large continental masses—the Northern Hemisphere continent, Laurasia (Laurussia in plate 3), and

the Southern Hemisphere continent, Gondwana. Laurasia includes modern-day Europe, Asia exclusive of the Indian subcontinent, Greenland, and North America. Gondwana includes modern-day South America, India, Australia, Africa-Arabia, and Antarctica.

The collision of Laurasia and Gondwana progressed from what is now north to south, along what is now the East Coast of North America, causing the uplift and formation of North America's Appalachians and Europe's Caledonian Mountains during the early phases of collision. Stresses from the collisions were transferred throughout the North American Plate. This led to uplift of blocks of crust in a currently northwest-southeast pattern, throughout the region that makes up present-day central and southwestern Colorado and southeastern Utah (plates 3 and 4). This created an ancient mountain range known as the Ancestral Rocky Mountains. These mountains were formed largely by uplift of large blocks of mountains, relative to other large blocks (deep sedimentary basins), along deep, near-vertical faults and, in places, thrust faults.

Remnants and evidence of the Ancestral Rocky Mountain uplifts are found in southwestern Colorado, as well as in Colorado's Front, Elk, and Sangre de Cristo Ranges. Numerous fractures and faults throughout the San Juan Mountains trend roughly parallel to the structural fabrics created during the uplift and development of the Ancestral Rocky Mountains. For example, the Snowdon Mountain block, in the Grenadier Range, was persistently a high area because of the resistant metamorphosed quartz-rich rocks exposed in this fault block.

The main evidence for the Ancestral Rocky Mountains, however, comes not from the mountains, because they were rather quickly eroded and covered by deposits of Permian–Jurassic age. Nor does it come from the faults, which tended to be reactivated and obscured by later mountain-building events. Instead, the best evidence comes from the very thick sedimentary deposits that filled basins adjacent to the uplifts (plate 4). As the fault-bound blocks of the Ancestral Rocky Mountains rose, erosion incised and wore away these highlands. This generated a vast accumulation of river and lake deposits in basins that flanked the highlands, such as the Paradox Basin. These deposits are preserved in rocks that are exposed in the region, such as the maroon-colored rocks of the Cutler Formation. The basins accumulated sediments near sea level, so these mountains might have been like modern-day mountainous areas of Greece, Italy, and the Aegean Sea—rugged uplifts cored by basement rocks but not as high above sea level as the present Rockies.

THE LARAMIDE ROCKY MOUNTAINS

During the Cretaceous, southwestern Colorado was covered by a vast inland seaway (plate 5). This seaway began a retreat as the Four Corners region once again underwent uplift, starting about 80 Ma and extending to perhaps 36 Ma (Cather 2004). During this pulse of mountain building, the Laramide orogeny, the western United

States was compressed and uplifted. In the Southwest, regional deformation of the crust caused broad uplift of the Colorado Plateau and an extensive north-south belt of ranges that form the Laramide Rocky Mountains. The Rocky Mountain belt attained some of its present elevation during the Laramide orogeny, although these mountains were extensively eroded before about 35 Ma and have experienced later periods of uplift.

In the Southern Rocky Mountains (figure 1.1), the Laramide orogeny created a series of mountain ranges and related structural sedimentary basins. In many areas, the mountain units are bound by upturned sedimentary rocks and bordered by steep reverse and thrust faults. The San Juan Mountains rest on part of the fault-truncated Sangre de Cristo Range to the east, the Sawatch Range to the north, and the San Juan Uplift (Needle Mountains Uplift) to the south (plate 1).

Along the southern edge of the San Juan Mountains, the Needle Mountains block was uplifted during the Laramide, as a result of compression and shortening, to form a domal structure that is elongated to the northeast. Cather (2004) discusses current ideas regarding the structural evolution of the San Juan Uplift and San Juan Basin. He summarizes recent evidence for dextral-transpressive deformation along the eastern margin of the Colorado Plateau in the development of Laramide uplifts and basins in the Southern Rocky Mountains, although the tectonics models for the Laramide orogeny in this region remain controversial (Seager 2004).

Paleozoic to Cenozoic sedimentary rocks are bent and tilted on the flanks of San Juan Uplift and are relatively flat-lying in the central part of the uplifted block. A deep bend on the southern edge of the Laramide uplift in southwestern Colorado created an asymmetrical syncline that defines the San Juan Basin (plate 1). This basin presents about 3,000 feet of structural relief and ~18,000 feet of structural relief between the Needle Mountains Uplift and the deepest part of the San Juan Basin (Kelley 1955). Cather (2004) reported that the evolution of the San Juan Basin involved diachronous subsidence and deposition, with at least three distinct periods of basin development.

The San Juan Basin is bound by abrupt and pronounced structural margins to the northwest (Hogback Monocline), northeast (southwest limb of the Archuleta Anticlinorium), and east (Nacimiento Uplift). In southwestern Colorado, tilted sedimentary strata of the Hogback define a flexure, partly fault-controlled, on the southern and eastern edges of the San Juan Uplift. As uplift of the Needle Mountains block continued into the Paleocene and Eocene, it was dissected by erosion that shed vast amounts of detritus as stream and fan deposits (Ojo Alamo Sandstone, Animas Formation, Nacimiento Formation, and San Jose Formation) into the San Juan Basin. Rock fragments in these deposits show a progressive uncovering of the uplifted block, down to its Proterozoic core. The Animas Formation also contains abundant fragments of volcanic rock, indicating the existence of volcanic centers to the north of the San Juan Basin prior to ~55 Ma.

At about 70 Ma, intermediate to felsic magmas rose into the crust, forming numerous mushroom-shaped bodies called laccoliths along the western edge of Colorado. Eroded remnants of Laramide laccolithic mountains in this part of the world include the La Plata, Abajo, and La Sal Mountains and smaller masses exposed on the fringes of the eastern San Juan Volcanic Field. These Laramide-intrusive complexes form the older component of a belt of Tertiary magmatism that extends from north-central into southwestern Colorado and that provided the loci of many mineralized deposits during the generation and development of the modern Rocky Mountains. Convincing geologic evidence (McCoy et al. 2005a; Tweto and Sims 1963) suggests that this belt, referred to as the Colorado Mineral Belt, has lineage in fractures and cracks that developed during the formation of Proterozoic mountain belts on the North American craton.

The widely accepted model (Dickinson 1981; Dickinson and Snyder 1978; Lipman, Prostka, and Christiansen 1971) for the Laramide orogenic event involves subduction that extended far inland, beneath North America's West Coast. In this "flat-slab," or shallow-subduction, model, the rate of subduction increased over time. This is thought to have caused the subducted slab to become more buoyant and rise to a lower angle beneath the North American Plate. This process caused "scraping" of the subducted plate 1,000 km inboard of the western edge of North America, leading to crustal compression and uplift (Dickinson 1981; Dickinson and Snyder 1978). Gutscher and colleagues (2000) offer convincing evidence for the flat-slab subduction in segments of the active subduction system of western South America. They argue that this process is caused by the subduction of buoyant oceanic plateaus, which allows the subducted slab to be driven up to 800 km from the active trench. Further deformation, up to 200 km inboard, is documented as block-type uplifts, or transpressional faulting for oblique convergence.

Other explanations for the formation of the Laramide Rocky Mountains have been proposed, but they have not provided substantial evidence to gain the support of most of the geosciences community. For example, Gilluly (1971, 1973) proposed that the Laramide orogeny was related to heterogeneities in the crust-mantle structure. Some recent studies provide evidence that forces in the earth at that time might have caused reactivation and movement along old fractures, which facilitated uplift and formed pathways for melted rock (Karlstrom and Humphreys 1998; Karlstrom et al. 2005; McCoy et al. 2005a, 2005b; Mutschler, Larsen, and Bruce 1987). In this model, the need for subduction as the catalyst for uplift and magmatism is less critical because magma production is dependent upon the release of pressure on the mantle to initiate melting rather than on the melting of the subducted oceanic slab. This is further supported by geophysical and geochemical studies that have concluded that the Laramide event did not have a substantial impact on the thermal state of the lithosphere; such an impact would be expected as a result of magmatism related to the proposed low-angle subduc-

tion that accompanied mountain building (Karlstrom et al. 2005; Livaccari and Perry 1993; Riter and Smith 1996).

McCandless and Johnson (2000) and McMillan (2004) note that although most of the geochemical and isotopic signatures of igneous rocks generated during this period are consistent with volcanic-arc systems, the temporal patterns of magmatism do not fully support this model. Furthermore, Gutscher and colleagues (2000) used geophysical data to argue that low-angle subduction creates a “cool thermal structure” in the lithosphere, which reduces heat flow and inhibits melting and arc magmatism. The more realistic model for Laramide magmatism may therefore involve some mechanism other than arc subduction.

THE SAN JUAN VOLCANIC FIELD

According to the flat-slab model, the rate of subduction involved in the formation of the modern Rocky Mountains slowed down at ~35 Ma. Foundering and sinking of the subducted plate to the west from its previous contact with the North American plate induced inflow of asthenospheric mantle, leading to widespread melting of the lithosphere and magmatism (Lipman, Prostka, and Christiansen 1971). This pulse of magmatism generated some of the largest volcanic eruptions in the Earth’s geologic record (plate 6; see also Lipman and McIntosh, chapter 2, this volume).

Oligocene magmatic events in the Four Corners region were linked to mantle-magma sources (Carlson and Nowell 2001; Farmer, Bailey, and Elkins-Tanton 2007; Johnson 1991; Lipman 2007; Lipman et al. 1978; Riciputi et al. 1995; Roden 1981). Evidence supports a model in which upwelling mantle magmas invaded the lithosphere and caused partial melting of the crust and extensive production of intermediate to felsic magmas. These magmas were the catalyst for the production of eruptive phases in the San Juan Volcanic Field (Farmer, Bailey, and Elkins-Tanton 2008; Johnson 1991; Lipman 2007). This regional magmatic-volcanic event is commonly called the “ignimbrite flare-up,” which was initiated farther west and north of the San Juan Mountains, although the San Juan Volcanic Field is a spectacular easterly expression of this process.

The ignimbrite flare-up resulted in the eruptions of large volumes of viscous, gas-rich magmas from about twenty caldera complexes preserved in the San Juan Volcanic Field (e.g., the Silverton–Lake City Calderas). Each caldera represents the collapse of land surface as a result of the massive expulsion of lava and ash. The calderas are inferred, on the basis of geophysical data (McCoy et al. 2005b; Plouff and Pakiser 1972), to be underlain by large volumes of granite that were emplaced at this time.

While mountain building by erupting magmas and accumulating volcanic deposits was somewhat localized, the ignimbrite flare-up also caused regional uplift of the Southern Rocky Mountains. Evidence for this is provided by analysis of the cooling histories of rocks in the Great Plains and in the Rockies, indicating that the

Southern Rocky Mountains were tilted up in a broad dome that caused additional erosion and uplift of the Rockies (Roy et al. 2004a, 2004b). This Oligocene contribution to the uplift of the Rockies was driven by deep-seated magmatism, and it resulted in broad doming of the region.

Current studies along the southern and western edges of the San Juan Mountains lend evidence for further jostling and uplift of blocks of the earth's crust at the onset of extensive volcanic eruptions of the San Juan Volcanic Field. During the early pulses of volcanic activity, as convincingly evident from field studies (Gonzales, Kray, and Gianniny 2005; Harraden and Gonzales 2007), the western San Juan Mountains, at least, were undergoing a renewed period of uplift. This uplift may reflect continued southwest-to-northeast compression (Cather 2004), but the mechanism of uplift is not well understood. Uplift was manifested in the reactivation of large blocks of crust that were eroded, leaving river gravels. These river gravels, called the Telluride Conglomerate, contain fragments of intermediate to felsic volcanic rocks similar to those found in the San Juan Volcanic Field, suggesting a contemporaneous series of events that must somehow be linked. The mountains were being uplifted and eroded as volcanic activity waned and rifting began in the region. Uplift between 40 and 30 Ma might have contributed to further elevation of the Needle Mountains and related subsidence in the San Juan Basin.

About 5 million years after this Early-Oligocene uplift and volcanism, crustal stretching and thinning began near the western and eastern boundaries of the San Juan Mountains. Incipient rifting was manifested in a southwest-to-northeast belt of potassium-rich mafic dikes and explosive diatreme volcanoes that formed as early as 28 Ma (Laughlin et al. 1986; Nowell 1993; Roden and Smith 1979). The eroded remnants ("necks") of these diatremes are exemplified by towers of dark-colored rock that dot the Navajo Volcanic Field. Ship Rock is the best-known of these iconic features. East of the San Juan Mountains, basin development along the Rio Grande rift indicates the onset of rifting between 35 and 30 Ma (Smith 2004) (plate 6). A series of generally north-south-trending mafic dikes located between Durango and Pagosa Springs (Gonzales 2009; Gonzales et al. 2006; Gonzales et al. 2010) may also provide further evidence for regional extension just after the onset of volcanism in the San Juan Volcanic Field, although the ages of these dikes are not constrained.

MID- TO LATE-TERTIARY ROCKY MOUNTAINS: LOCAL COLLAPSE OF HIGH TOPOGRAPHY

The Southern Rocky Mountains of New Mexico continued to undergo extension in an east-west direction between 25 and 10 Ma. This continental rifting overlaps in timing with the formation of extensional structures of the Basin and Range province, although the location of the north-south rift—parallel to the north-south Rocky Mountains uplift—and the fact that the rifting decreases in magnitude northward

suggest that it was driven in part by gravitational collapse of the high mountains that had formed earlier. The Rio Grande Rift is not well-developed northward in Colorado, although the active extension is still ongoing, as indicated by the hot springs, high heat flow, and young faulting along the Arkansas Valley and in other areas east of the San Juan Mountains.

Is uplift of the San Juan Mountains ongoing? This region is underlain by some of the lowest-velocity crust found anywhere—the Aspen anomaly (Karlstrom et al. 2005). The Aspen anomaly is characterized by a mantle zone similar in shape and character to each of those found in the Yellowstone and Jemez (Valles) hot-spot anomalies. These other areas are associated with recent (< 1 Ma) caldera eruptions, whereas the Aspen anomaly is not—yet. Mantle gases detected in hot springs throughout and adjacent to the northern San Juan Mountains (Newell et al. 2005) suggest young and active mantle upwelling beneath the region. Reiter (2008) provides evidence from thermal- and gravity-anomaly sources for a contribution to current uplift in the San Juan Mountains, from upper-mantle buoyancy. One view is that the very rugged nature of the San Juan Mountains reflects erosion responding to this ongoing uplift; another model is that relatively wet climates during the last few million years have caused increased erosion of a previously elevated region.

THE FUTURE OF THE SAN JUAN MOUNTAINS

In the past several million years, the San Juan Mountains have been worn and sculpted by the active erosive forces of glaciers and rivers. Removal of crustal mass may be facilitating minor uplift. This erosion has also exposed windows into the crust, allowing geologists to study older rocks and gain insight into the mountain-building processes responsible for (1) formation of the continent, as recorded by the contorted deep-crustal roots of a series of planed Precambrian mountain belts; (2) formation of the Ancestral Rocky Mountains by Paleozoic plate collisions; (3) formation of the modern Rocky Mountains by Laramide compression and uplift; (4) the San Juan Volcanic Field and concurrent uplift; and (5) ongoing uplift related to continued mantle buoyancy, the Rio Grande Rift, and mantle degassing associated with the Aspen anomaly.

The southwestern United States is undergoing widespread stretching and extension as the Pacific and North American plates interact along the San Andreas Fault in California. In tens of millions of years, the San Juan Mountains may also be dismembered by this process, forming a landscape similar to that of the Basin and Range country in Nevada and in western and southern Arizona. The Rio Grande rift may be unzipping northward. Alternatively, the partially melted mantle zone known as the Aspen anomaly may herald a future caldera eruption similar to Yellowstone, the Jemez Caldera, and the San Juan calderas before them. If so, uplift and building of mountains may continue. The question of whether the San Juan Mountains are presently going up, as a result of mantle uplift, or down, as a result

of erosion, is unresolved. Eventually, the San Juan Mountains will be eroded to base level, as were the Precambrian arc mountains and the Ancestral Rockies.

Whatever the future holds for the San Juan Mountains, cycles of mountain building and beveling will continue as plate tectonics and erosion transform layers of crust into the yet-unwritten pages of Earth's history.

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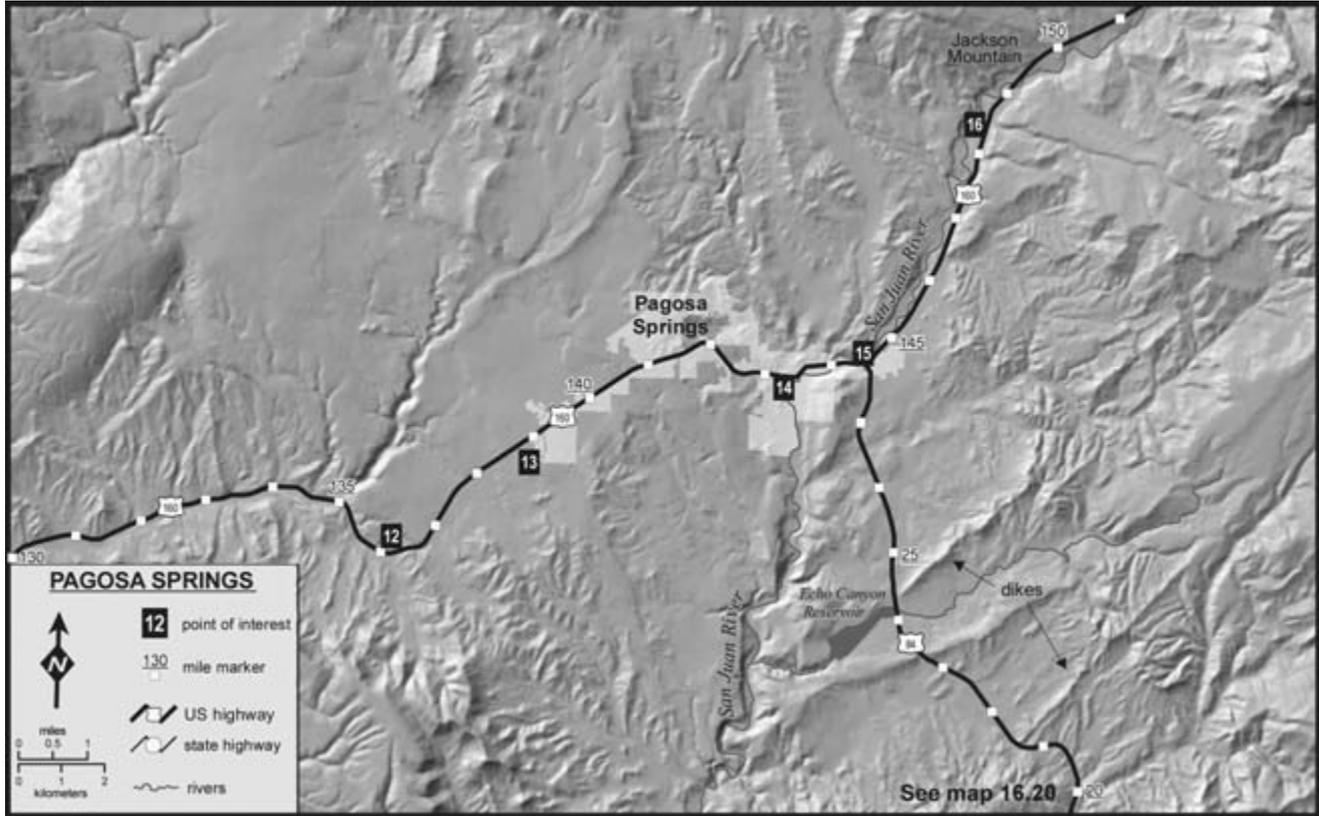
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MAP 16.1 Durango (POI 1-5)



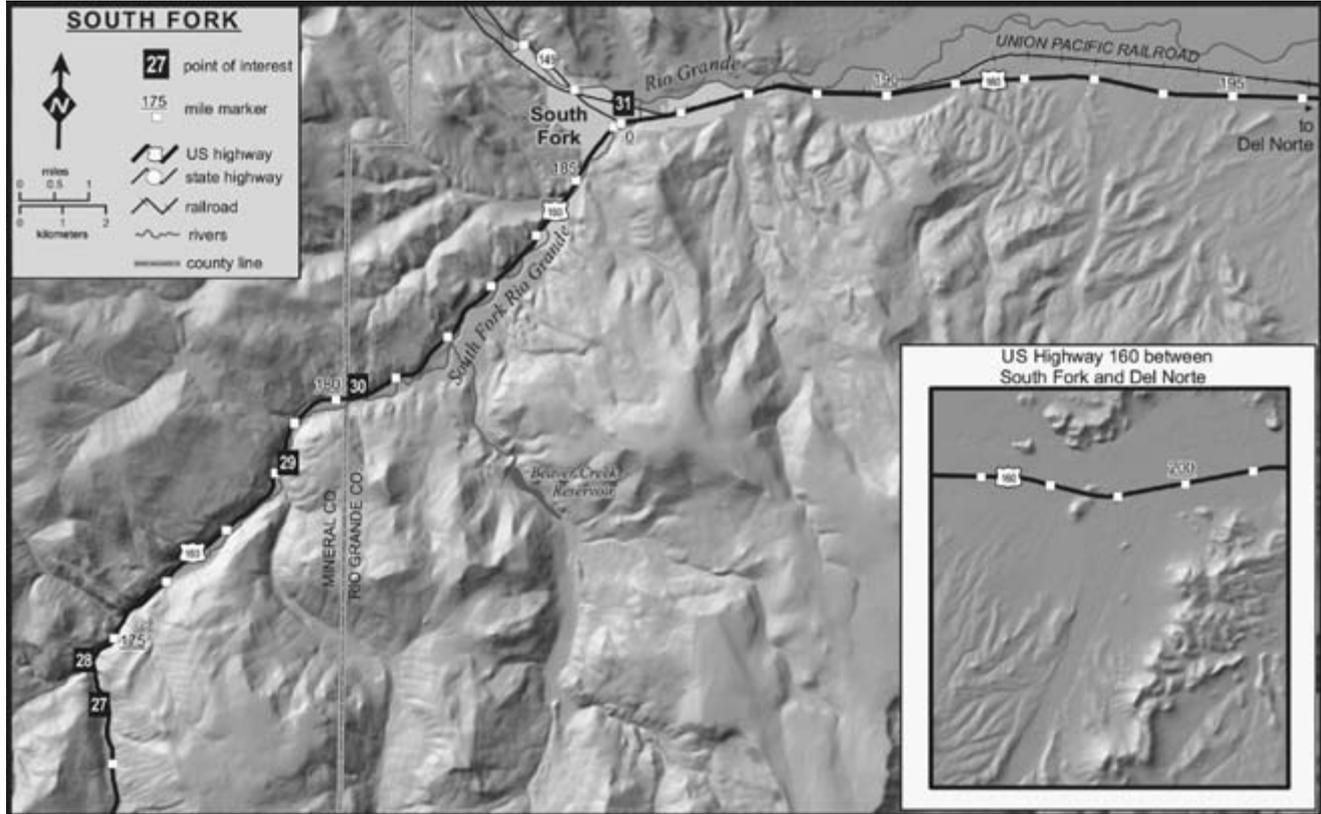
MAP 16.2 Chimney Rock (POI 6–11)



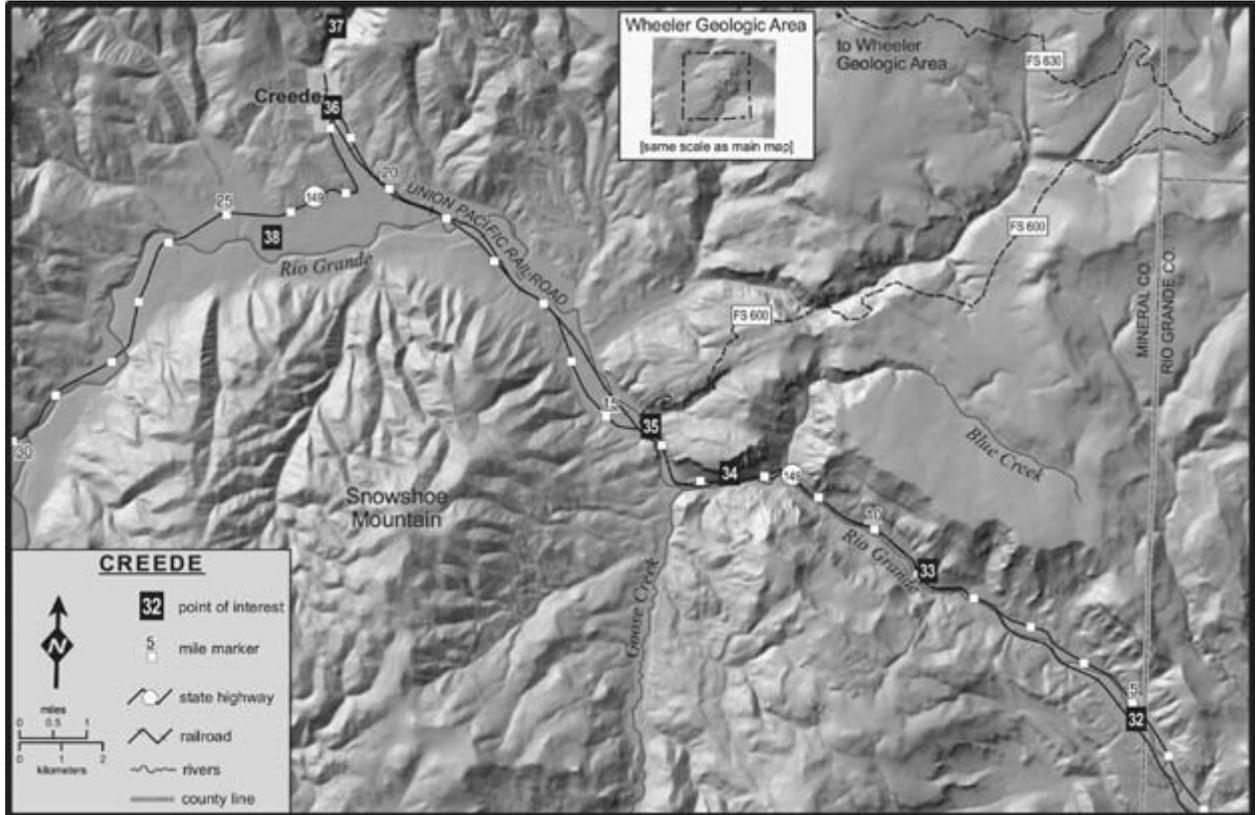
MAP 16.3 Pagosa Springs (POI 12–16)



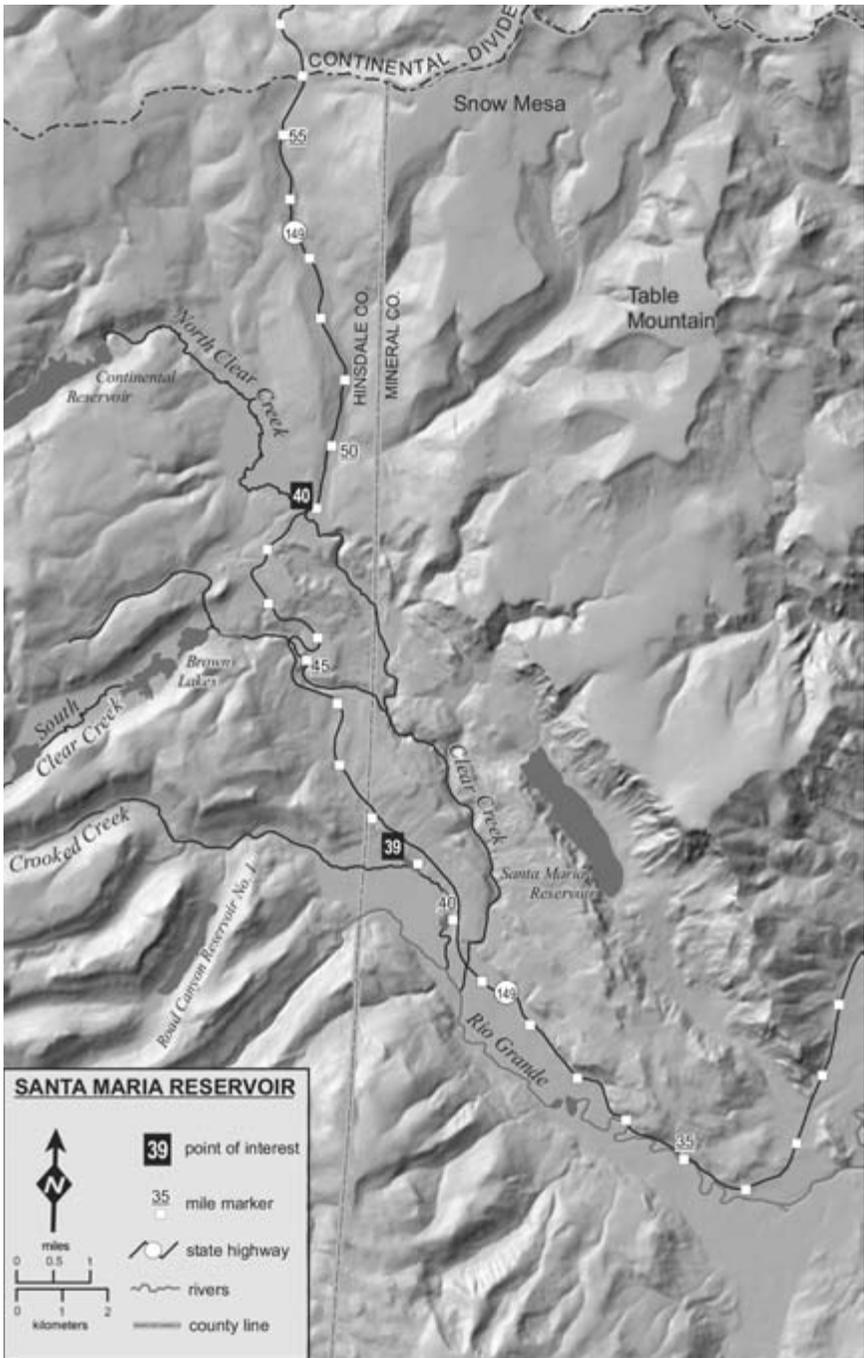
MAP 16.4 Wolf Creek Pass (POI 17–26)



MAP 16.5 South Fork (POI 27–31)



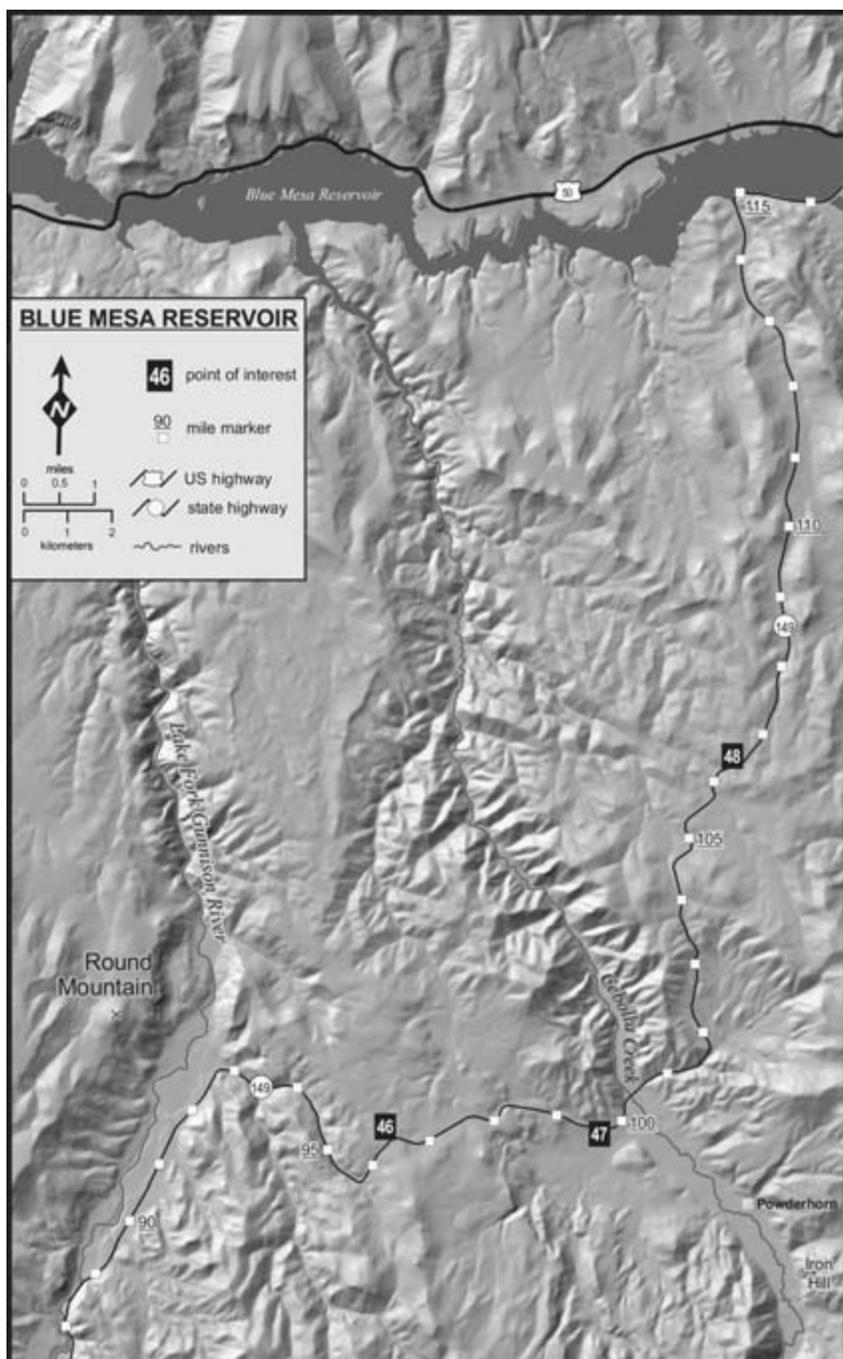
MAP 16.6 Creede (POI 32–38)



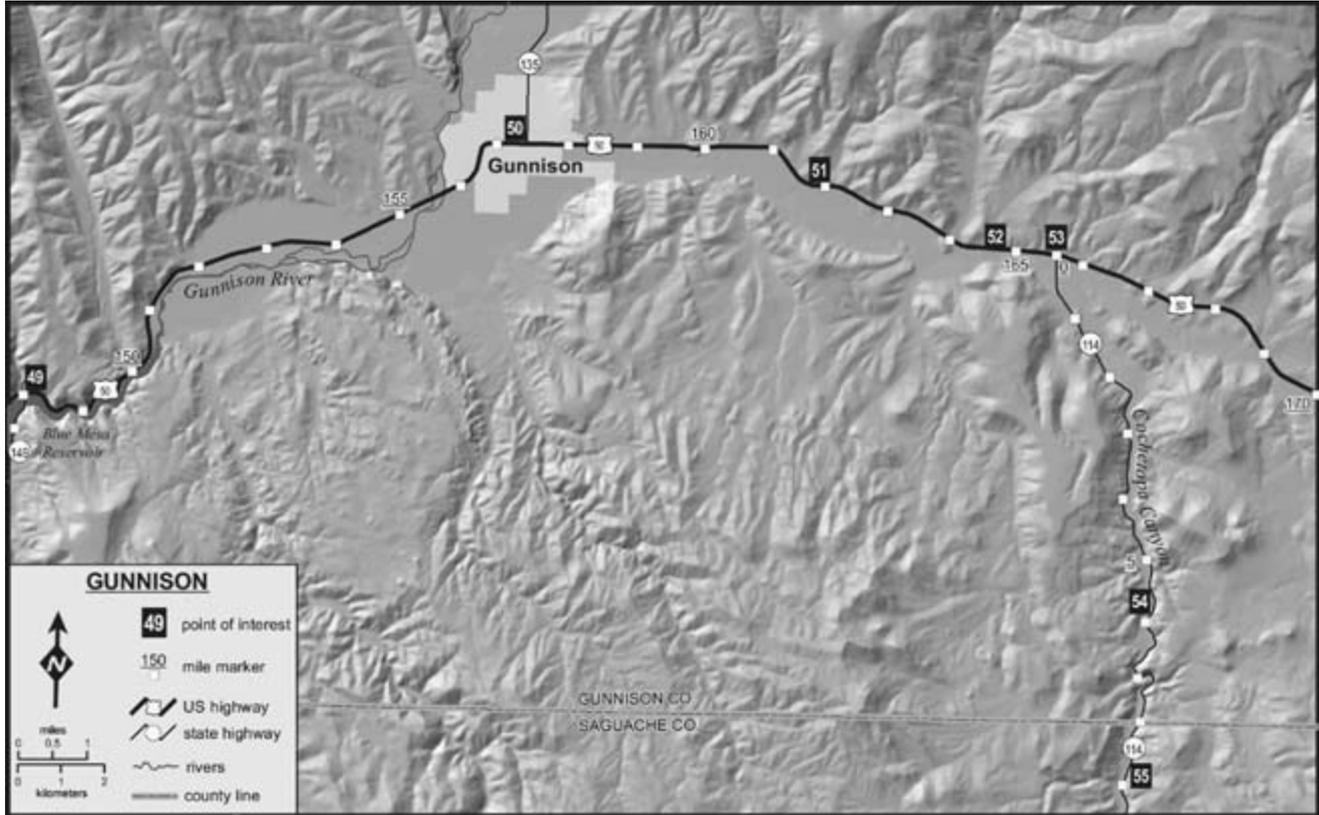
MAP 16.7 Santa Maria Reservoir (POI 39-40)



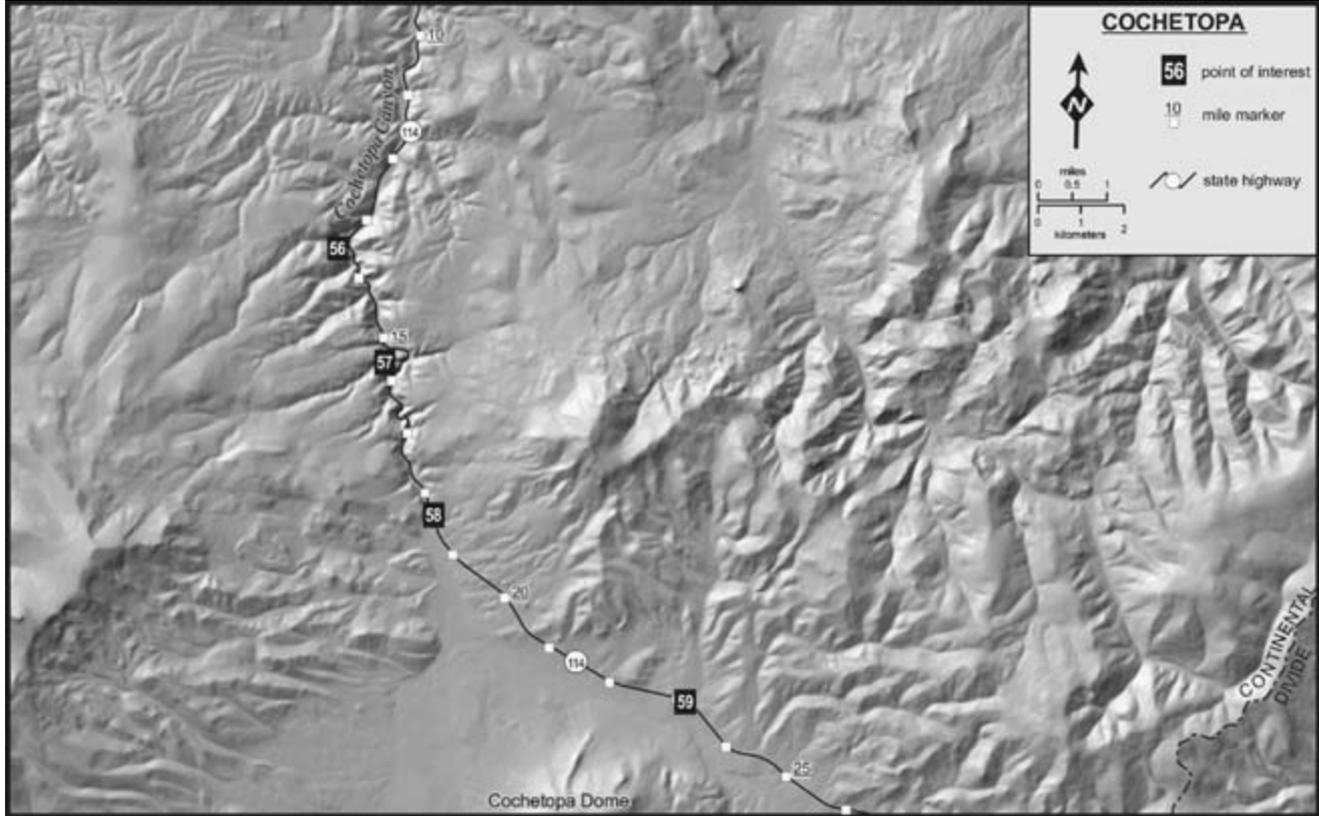
MAP 16.8 Lake City (POI 41–45)



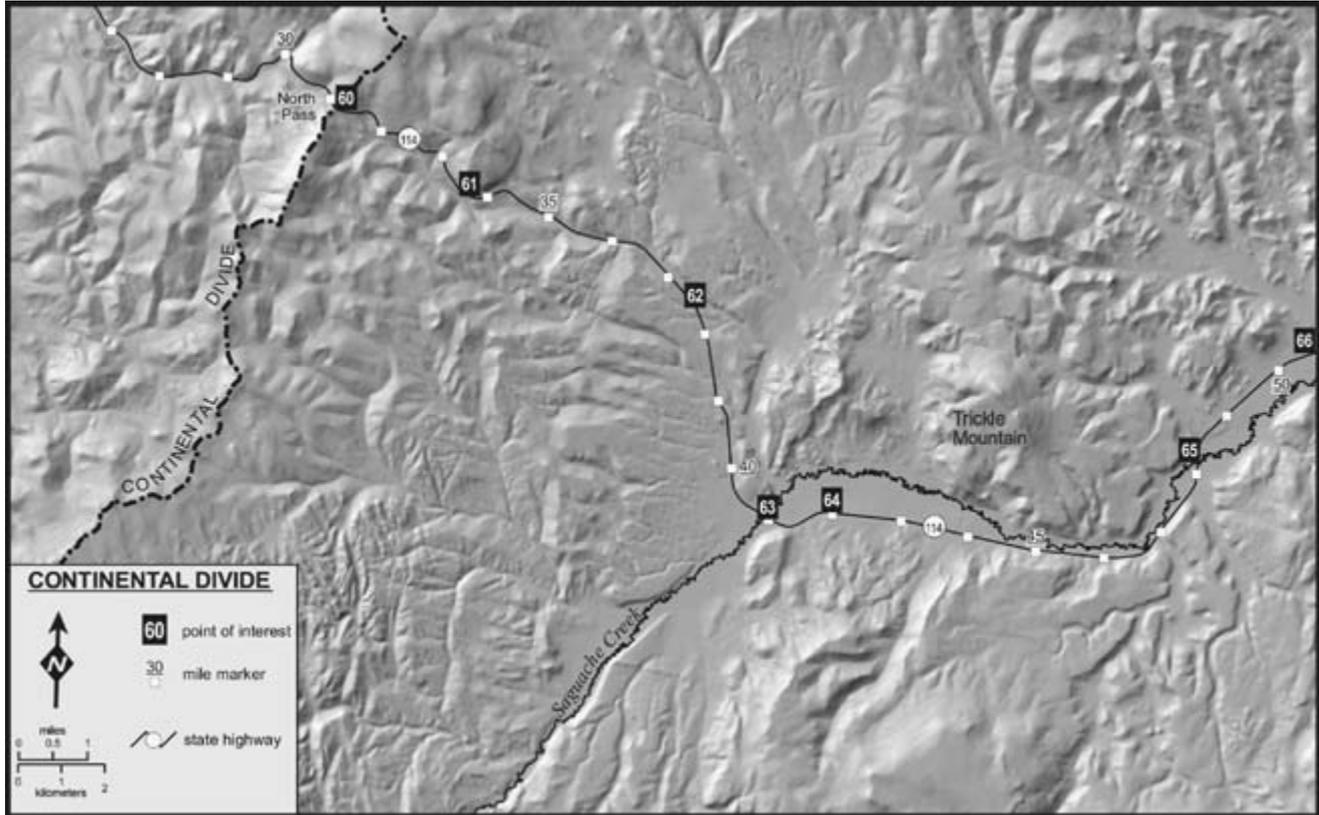
MAP 16.9 Blue Mesa Reservoir (POI 46–48)



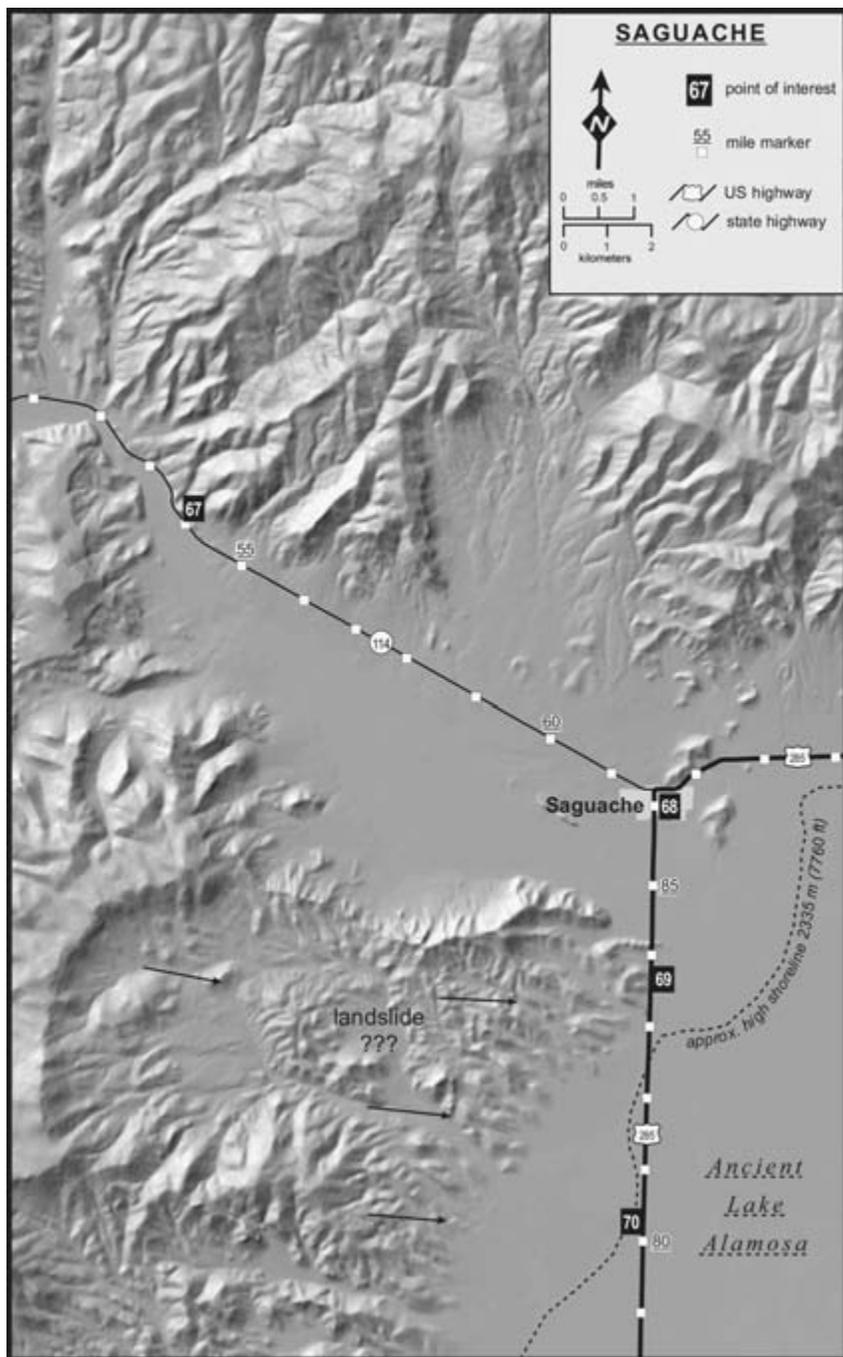
MAP 16.10 Gunnison (POI 49–55)



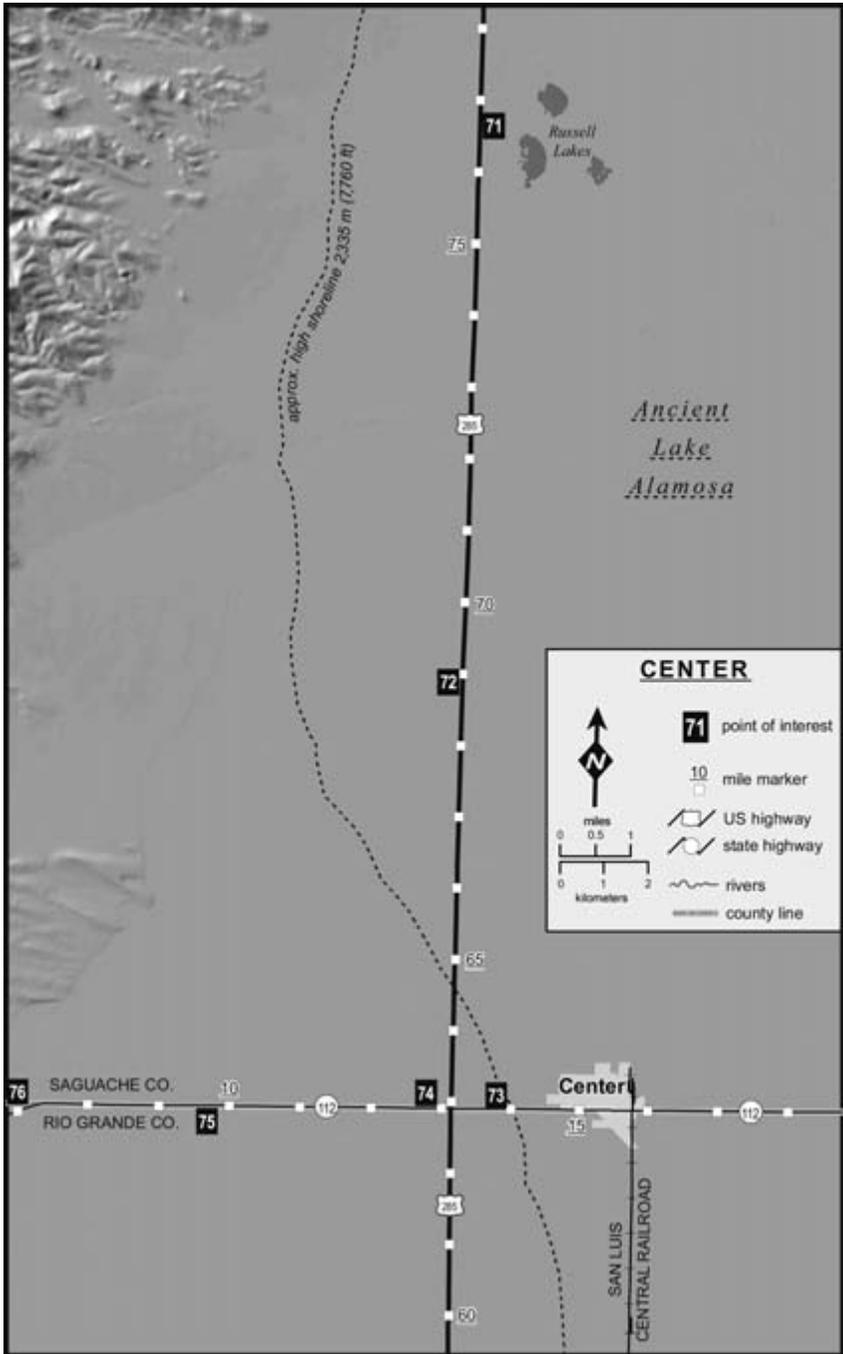
MAP 16.11 Cochetopa (POI 56–59)



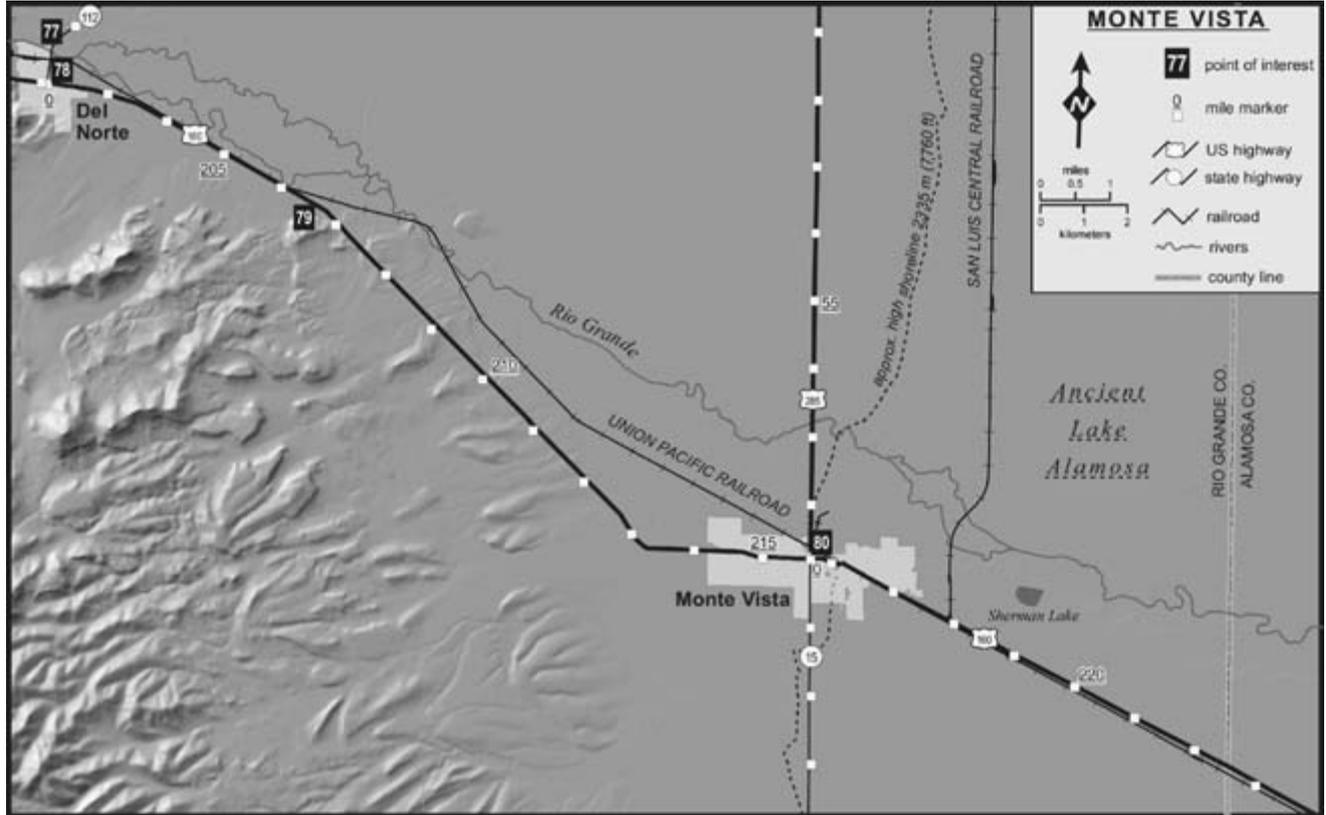
MAP 16.12 Continental Divide (POI 60–66)



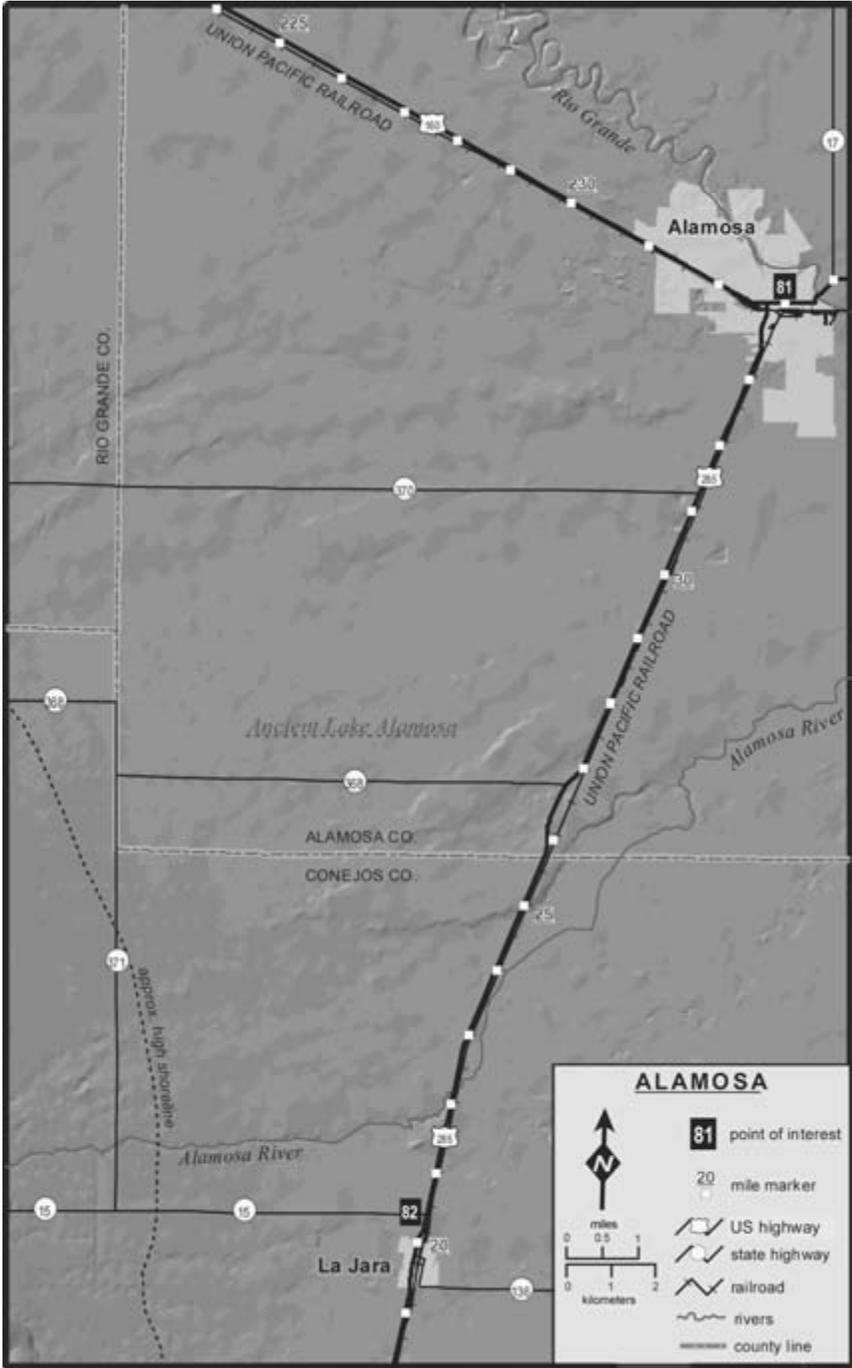
MAP 16.13 Saguache (POI 67–70)



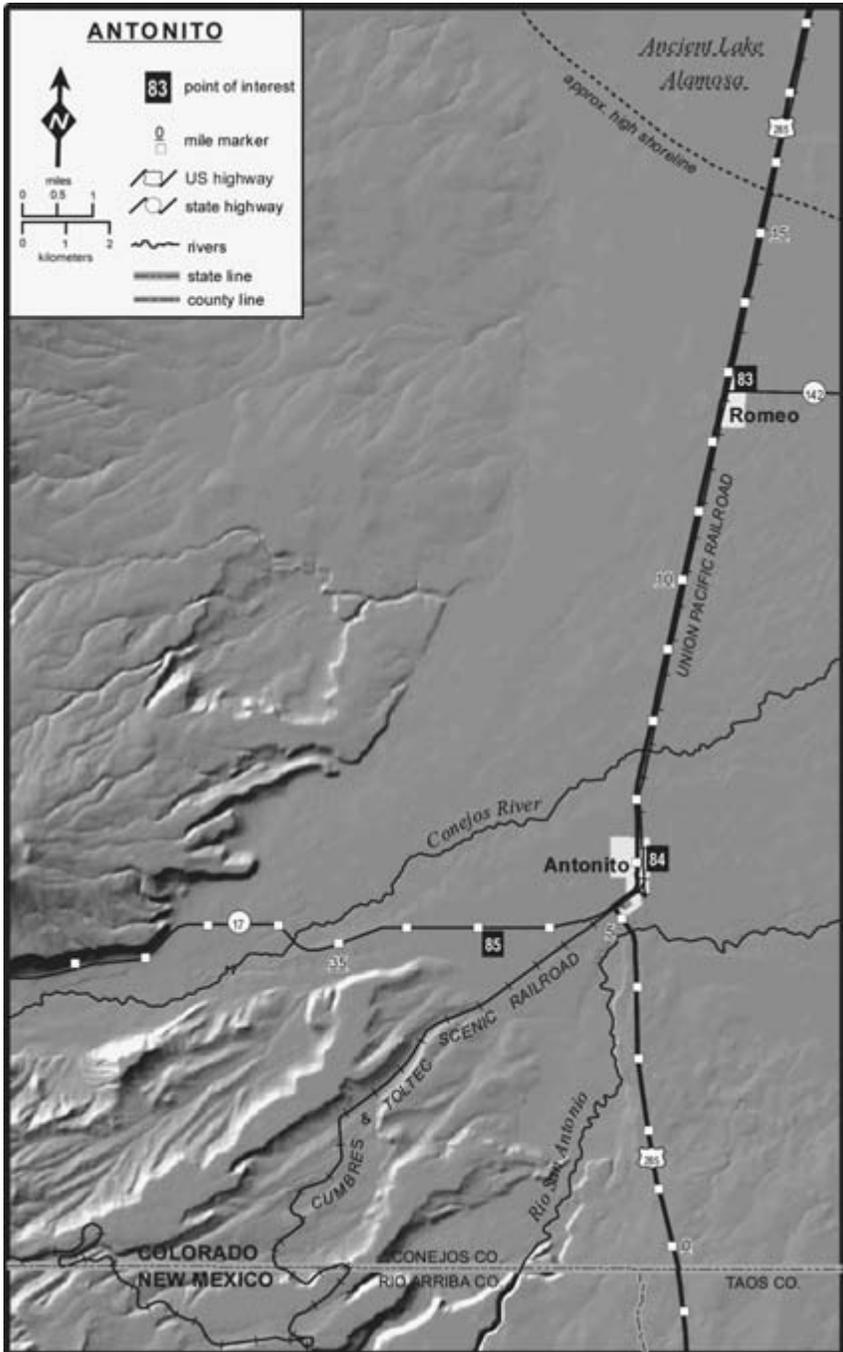
MAP 16.14 Center (POI 71-76)



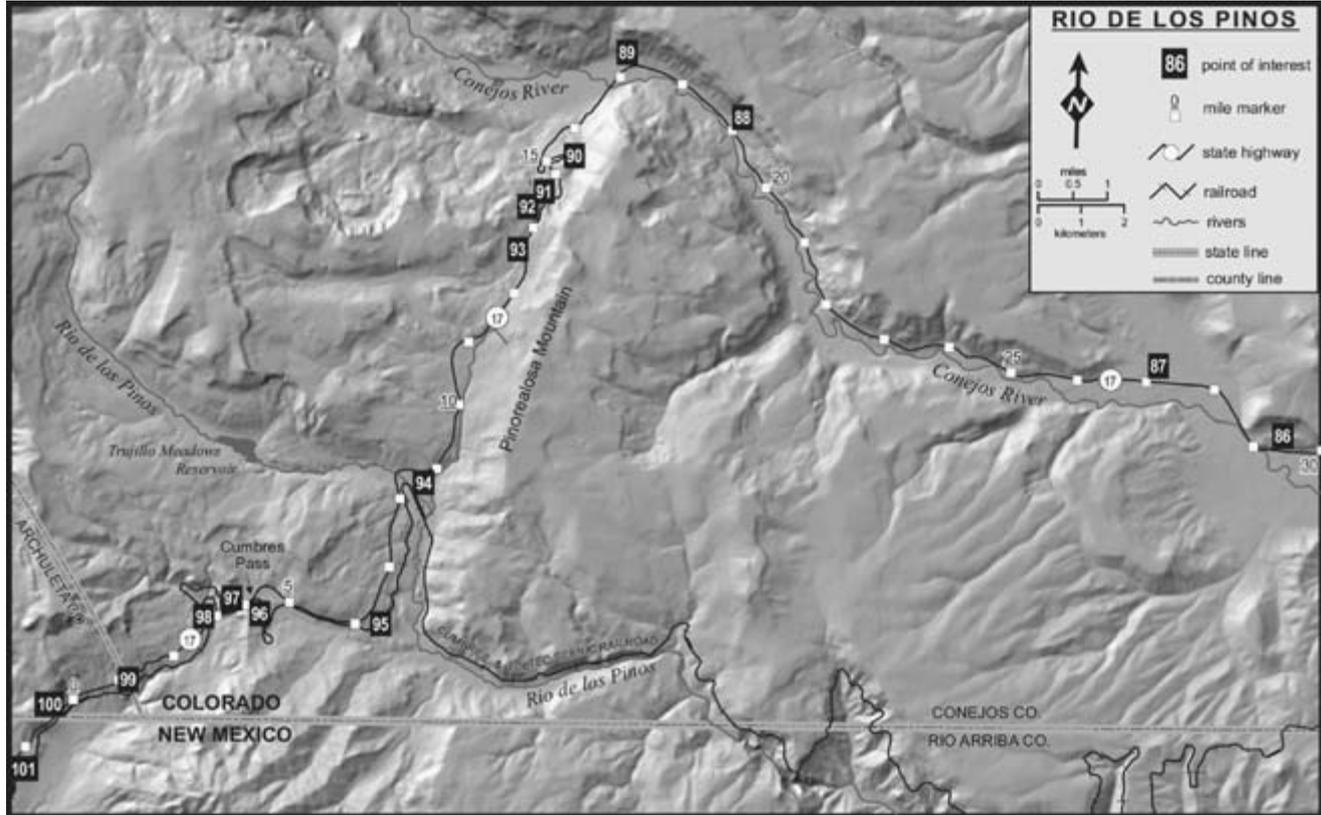
MAP 16.15 Monte Vista (POI 77-80)



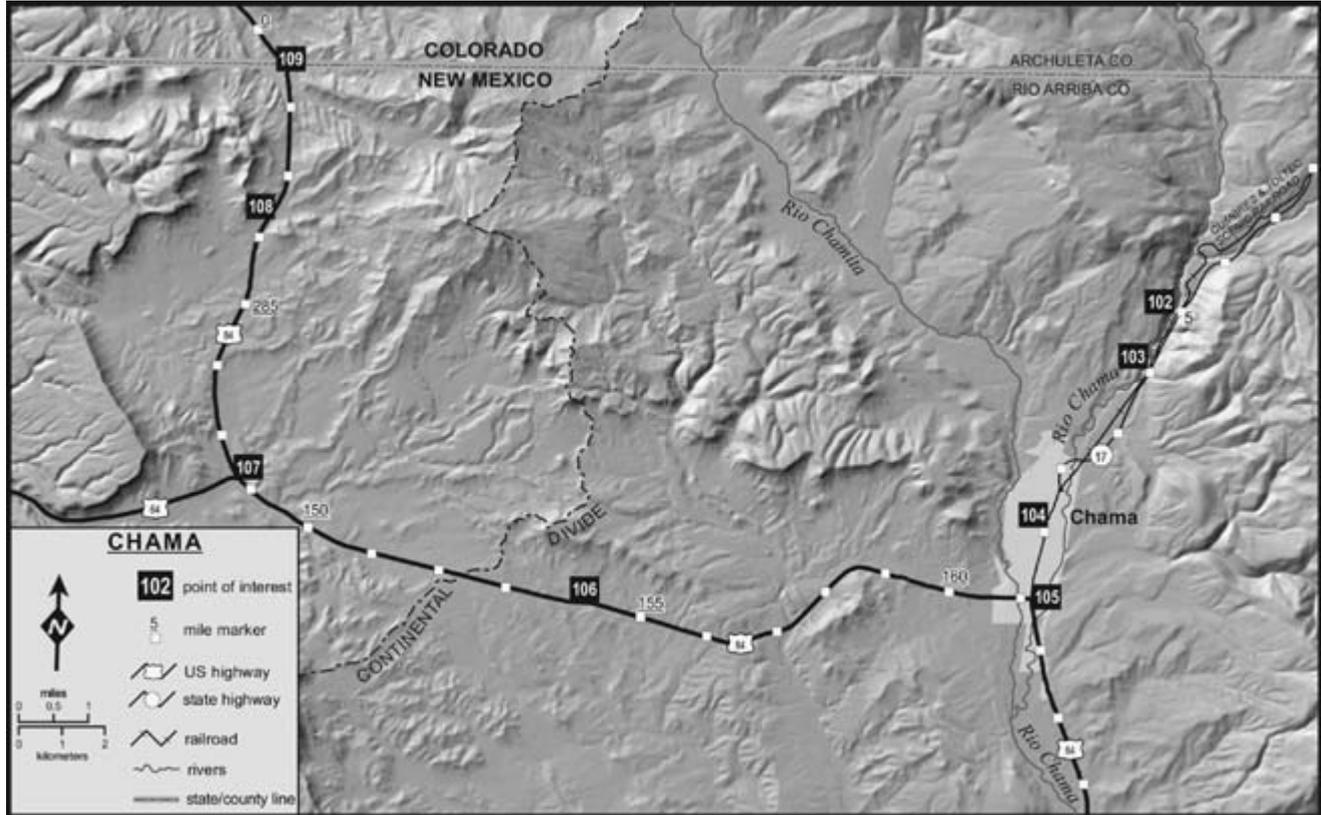
MAP 16.16 Alamosa (POI 81-82)



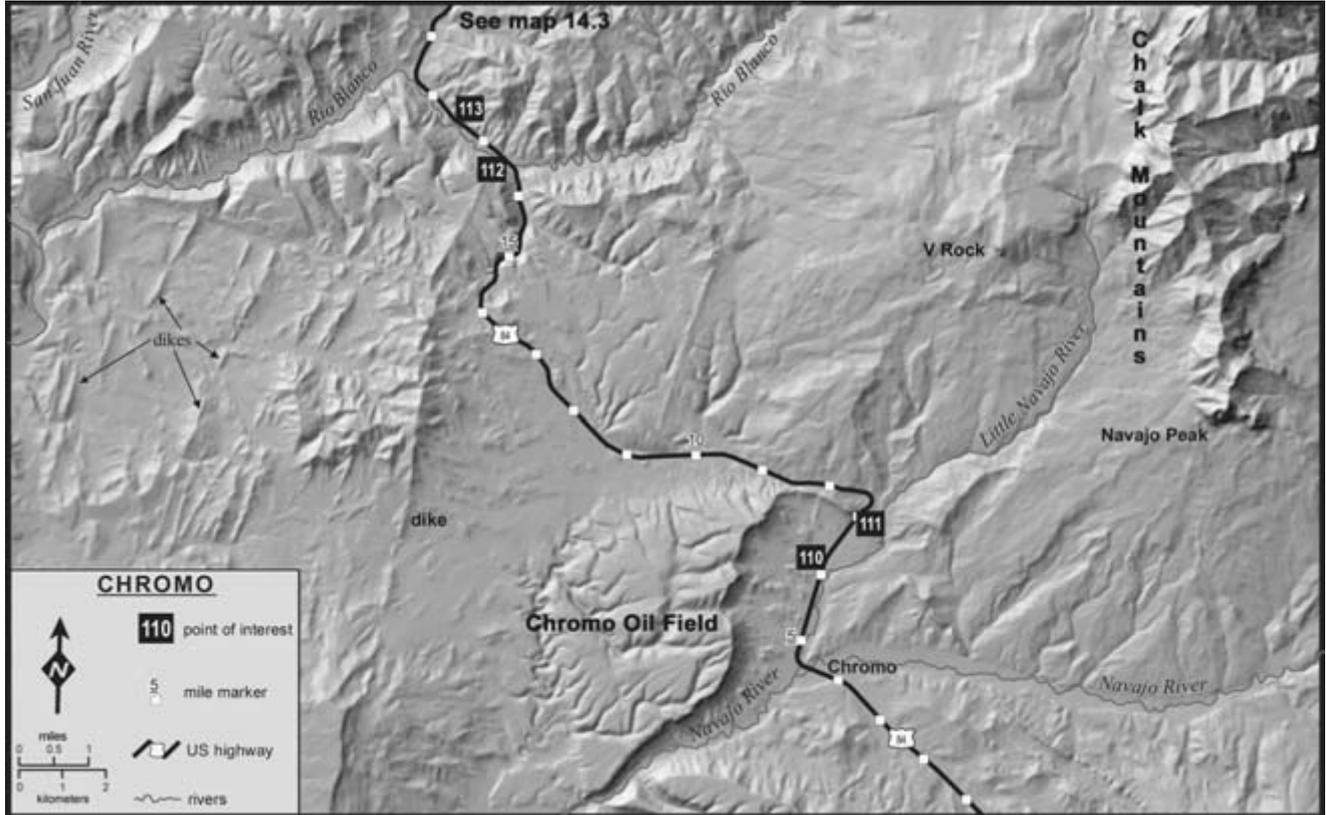
MAP 16.17 Antonito (POI 83–85)



MAP 16.18 Rio de los Pinos (POI 86–101)



MAP 16.19 Chama (POI 102–109)



MAP 16.20 Chromo (POI 110–113)