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Introduction to late Cenozoic evaporite tectonism and volcanism in west-central Colorado

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ABSTRACT

Recent cooperative mapping and investigations by the Colorado Geological Survey and U.S. Geological Survey in west-central Colorado provide evidence for regional evaporite tectonism and related collapse that have operated from the late Cenozoic to the present. These studies document as much as 1200 m of vertical collapse caused by subsurface dissolution and flow of the Pennsylvanian Eagle Valley Evaporite in an area of at least 3600 km^2 and possibly >5000 km^2. During the late Cenozoic, rivers removed an estimated 2300 km^3 of dissolved evaporite from the contiguous Carbondale and Eagle collapse centers.

Quantitative evidence for these collapse processes was found by 1:24 000-scale geologic mapping and supporting topical studies that primarily focused on (1) late Cenozoic volcanic stratigraphy (2) late Cenozoic incision rates, and (3) subsurface rock character and structures. The base of widespread basaltic and minor silicic volcanic rocks defines a late Oligocene to early Miocene, low-relief paleosurface that contrasts with the modern rugged topography. Elevation differences between the present positions of volcanic rocks within areas affected by collapse and the dated paleosurface outside the collapsed areas quantify the collapse in the region.

Evaporite flow probably began shortly after burial of the evaporite by overlying deposits, has continued episodically at least into the middle Quaternary based on diapiric tilting of Pleistocene river terraces, and probably still continues. Evaporite dissolved by groundwater discharges directly to the surface-water system from both hot and cold springs. Saline groundwater also seeps into alluvial aquifers and eventually mixes with surface water.

INTRODUCTION

For nearly half a century scientists have reported evidence of localized evaporite flow and dissolution in west-central Colorado (see section on previous studies). Recent cooperative geologic mapping of 7.5-minute quadrangles (Fig. 1) and supporting investigations by the Colorado Geological Survey (CGS) and U.S. Geological Survey (USGS) have expanded knowledge of evaporite tectonism in west-central Colorado. These studies document the timing, regional extent, amount of vertical collapse, volume of evaporite removal, and geometry and mechanism of collapse. As used throughout this book, evaporite tectonism includes crustal deformation related to both flow and dissolution of evaporite. Flow can cause either removal of evaporite, which results in subsidence and collapse, or thickening of evaporite, which causes upwelling and local

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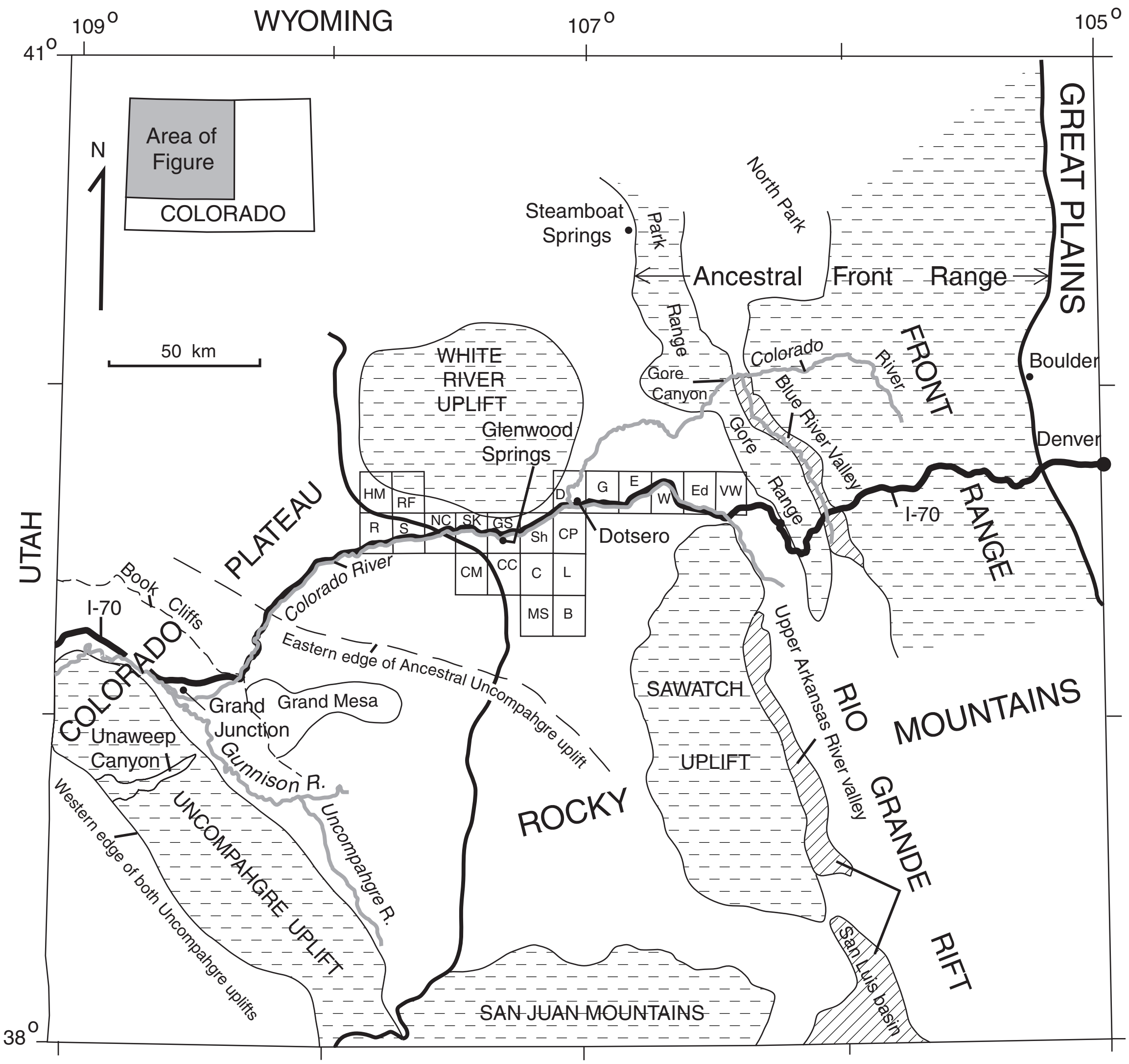

Figure 1. Regional map showing geographic and geologic features in part of west-central Colorado. The small rectangles identify 7.5′ quadrangles mapped in the area of collapse mapped by the USGS and CGS. HM—Horse Mountain (W.P. Perry, 2001, written commun., geologic map); RF—Rifle Falls (Scott et al., 2001); R—Rifle (Shroba and Scott, 1997); S—Silt (Shroba and Scott, 2001); NC—New Castle (Scott and Shroba, 1997); SK—Storm King Mountain (Bryant et al., 1998); CM—Center Mountain (Carroll et al., 1996); GS—Glenwood Springs (Kirkham et al., 1997a); CC—Cattle Creek (Kirkham et al., 1996), Sh—Shoshone (Kirkham et al., 1995); C—Carbondale (Kirkham and Widmann, 1997); MS—Mount Sopris (Streufert, 1999); D—Dotsero (Streufert et al., 1997a); CP—Cottonwood Pass (Streufert et al., 1997b); L—Leon (Kirkham et al., 1998); B—Basalt (Streufert et al., 1998); G—Gypsum (M.R. Hudson, 2001, written commun., geologic map); E—Eagle (Lidke, 2002); W—Wolcott (Lidke, 1998); Ed—Edwards (D.J. Lidke, 2001, written commun., geologic map); VW—Vail West (Scott et al., 2002). Heavy lines that run generally north-south mark the approximate locations of physiographic boundaries.

diapirism that produces uplift. Dissolution causes only subsidence or collapse of overlying strata.

The CGS initiated a 1:24 000-scale geologic mapping program in the Glenwood Springs–Carbondale area in 1993, and the USGS began its mapping and supportive research program along the Interstate Highway 70 corridor, both east and west of the CGS map area, in 1995. Early during CGS and USGS investigations, the team recognized that evaporite tectonism played a major role in the late Cenozoic tectonic events in the region. Scientists from both agencies also realized that a thorough knowledge of late Cenozoic volcanic stratigraphy could provide critical time and spatial constraints on the evaporite tectonism when added to the mapped geologic framework. USGS-CGS investigations immediately focused on the evaporite deformation and late Cenozoic volcanic stratigraphy using $^{40}Ar/^{39}Ar$ geochronology, major- and trace-element geochemical analyses, petrographic studies, and paleomagnetic investigations.

Early in the study, K.A. Hon (formerly with the USGS) recognized that flow structures in steeply dipping basaltic flows in the Carbondale area required that lavas originally erupted onto relatively flat topographic surfaces and subsequently were tilted. Also during this initial period of study, we recognized the enigmatic geomorphic relations between a 22.4 Ma basaltic flow near the elevation of the Roaring Fork River and 7.8 to 10 Ma basaltic rocks located in adjacent highlands as much as 1 km higher (Kirkham et al., 1995, 1996, 1997a). These relationships could not be explained by prior interpretations of the late Cenozoic history of the region (Larson et al., 1975) and required that some type of structural deformation affected the flows.

Joint discussions that focused on the origin of the deformation discounted tectonism associated with rifting as a possible causative mechanism, so an alternative hypothesis was developed. We proposed that the most logical explanation of this deformation was geologic collapse of the lava flows as a result of dissolution of underlying evaporite. T.A. Steven (USGS emeritus, 1996, personal commun.) pointed out that Miocene basaltic rocks outside areas of suspected collapse were at elevations of 2.9–3.4 km. We hypothesized that the basaltic flows within the collapsed areas originally stood at equivalent elevations prior to collapse and that this locally basalt-capped surface was a datum from which we could quantify evaporite collapse. We also jointly acquired seismic reflection lines and conducted paleomagnetic studies of basaltic flows to test our collapse hypothesis.

The investigations quickly led to the recognition of two contiguous evaporite collapse areas (Fig. 2). The Carbondale collapse center includes much of the lower Roaring Fork River valley between Glenwood Springs and Mount Sopris and also an elongate arm that follows the Grand Hogback monocline northwestward from Glenwood Springs. The Eagle collapse center covers all the lower areas between Minturn, Yarmony Mountain, the White River uplift, Dotsero, Basalt Mountain, and the Sawatch uplift, with the possible exception of a small topographic high near Castle Peak.

Evaporite deformation readily occurs under conditions and by mechanisms that do not cause most sedimentary rocks to deform. Halite, gypsum, and anhydrite have well-known physical and chemical properties that facilitate the collapse process. They are soluble in fresh water, are ~10% less dense than most clastic sedimentary rocks, and readily change shape by recrystallizing, particularly if there is sufficient intercrystalline water to allow diffusional mass transfer (Williams-Stroud and Paul, 1997). Relatively minor differences in confining pressures will cause these phases to flow from high confining pressures toward lower confining pressures. Therefore, any process that creates sufficient differential confining pressures, such as (1) deposition of a differential load of relatively dense and thick overburden above an evaporite layer, (2) application of compressional or extensional stresses on a rock package that includes significantly thick layers of evaporites sandwiched between relatively rigid rocks, or (3) deep incision of relatively narrow stream valleys into rocks above evaporite layers, can induce deformation.

This volume addresses late Cenozoic evaporite tectonism and volcanism in west-central Colorado. Kirkham et al. (this volume) discuss abundant evidence of late Cenozoic evaporite deformation in the Carbondale collapse center in the lower Roaring Fork River valley. Scott et al. (this volume) focus on collapse in the absence of a basaltic "datum" on the southwest flank of the White River uplift in a northwestern part of the Carbondale collapse center. Lidke et al. (this volume) report features of the Eagle collapse center that provide evidence both for late Cenozoic collapse and for older evaporite deformation. Chafin and Butler (this volume) evaluate the dissolved-solids load in rivers, and Mock (this volume) describes the geologic setting and hazards of evaporite sinkholes.

This volume also emphasizes investigations that define the nature of the critical basaltic datum. Kunk et al. (this volume) present the $^{40}Ar/^{39}Ar$ geochronology of the Cenozoic volcanic rocks. Budahn et al. (this volume) provide and interpret the major- and trace-element geochemical data that are used to correlate flows and eruptive centers and to evaluate possible relationships between genesis of basaltic magmas, uplift, and late Cenozoic rifting. Hudson et al. (this volume) explain how the paleomagnetic character of the basaltic rocks restricts structural interpretations of suspected collapse areas.

Several chapters cover topics that compliment this framework. Naeser et al. (this volume) give evidence for Neogene uplift in the Gore Range and adjacent areas, which provides a possible explanation for initiation of deep incision of streams in the area. Steven (this volume) submits regional evidence for late Cenozoic uplift adjacent to collapsed areas and proposes uplift as the primary cause of increased stream incision. Perry et al. (this volume) evaluate the subsurface expression of evaporite tectonism by interpreting seismic reflection data.

Previous studies

Local evidence of evaporite flow and dissolution in west-central Colorado was described in several previous studies dating back to the middle of the 20th century. Hubert (1954) attributed ~300 m of relief on late Tertiary basaltic flows near Eagle to "adjustment of the underlying gypsum." Wanek (1953) recognized ~900 m of subsidence in late Tertiary basaltic flows and interbedded lacustrine sediments southeast of State Bridge. Benson and Bass (1955) proposed a diapiric origin for a valley anticline in the Eagle collapse center beneath the Eagle River between Dotsero and Gypsum. The axis of a valley anticline underlies and is roughly parallel to the valley. Bass and Northrop (1963) attributed a tightly folded syncline in upper Cenozoic sedimentary deposits northwest of Glenwood Springs to "subsidence into caverns in the underlying thick gypsum beds."

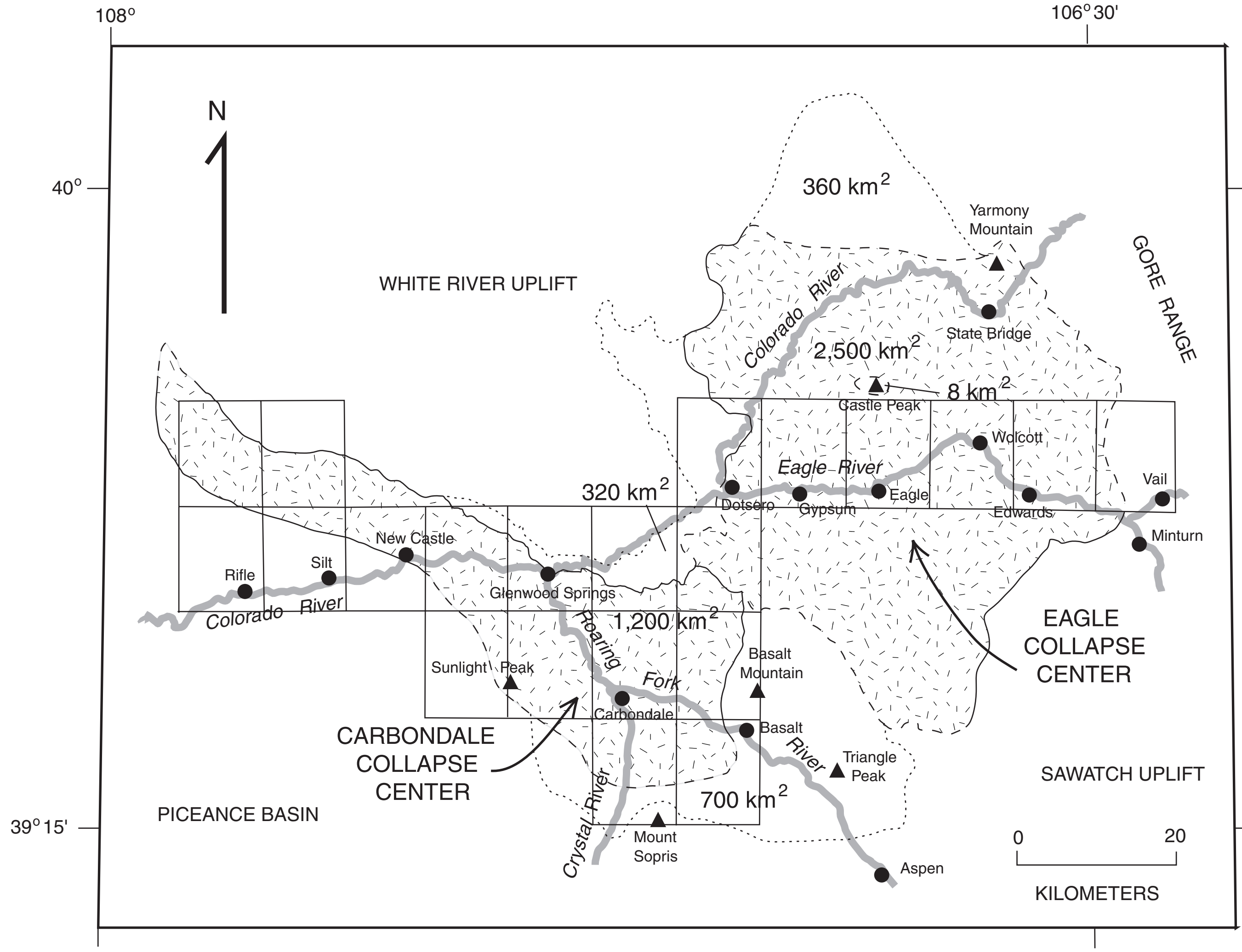

Figure 2. Map showing areas of known and suspected collapse in the Carbondale and Eagle collapse centers. Areas with strong evidence of collapse are patterned, and they are outlined by solid lines where well constrained and by dashed lines where less certain. Dotted lines denote areas of suspected collapse where evidence is equivocal. Boxes outline quadrangles recently mapped by the CGS and USGS.

As part of a regional study of the Eagle Valley Evaporite, Mallory (1966, 1971) reported two areas with thick evaporite, one near Carbondale and a second near Eagle. He also described the diapiric Cattle Creek anticline along the lower Roaring Fork River valley, which is cored by evaporite. Murray (1966, 1969) recognized prominent flexural-slip faults that were related to late Cenozoic partial unfolding of strata previously folded by the Grand Hogback monocline. He rejected the hypothesis that this unfolding was due to northeastward collapse of the monocline in response to salt dissolution, but acknowledged that flow of evaporite from beneath the monocline could explain the unfolding. Freeman (1971, 1972) recognized abrupt thickness changes in formations and unconformities between formations that overlie the evaporitic rocks, and he speculated that diapiric upwellings of evaporite could cause such phenomena. Tweto (1977) suggested large-scale flow of evaporite was responsible for the local, but thick accumulations of the Permian and Triassic State Bridge Formation and Pennsylvanian and Permian Maroon Formation.

Larson et al. (1975) studied the late Cenozoic basaltic rocks of northwest Colorado using K-Ar dating, geochemistry, and paleomagnetism. They attributed the occurrence of post-10 Ma basaltic rocks at low elevations to intermittent post-10 Ma river incision. However, they were not aware of relationships that contradicted their premise: Miocene volcanic rocks occur at low elevations along the valleys in this area (Kirkham et al., this volume; Lidke et al., this volume).

Piety (1981) documented fracturing, faulting, and local tilting of Pleistocene terraces along the Roaring Fork River. Soule and Stover (1985), Stover (1986), and Unruh et al. (1993) also mapped or discussed the flexural-slip faults along the Grand Hogback monocline. De Voto et al. (1986) gave a thorough description of the late Paleozoic stratigraphy and syndepositional tectonism related to the Pennsylvanian evaporite.

Although the literature on salt tectonism is extensive, none uses deformation of Neogene basalts to quantify the magnitude of collapse or volume of evaporite removed from the area. Christiansen (1971), Gustavson (1986), Johnson (1989), and Ford (1997) described thickness changes in formations in Canada and the United States that resulted from evaporite tectonism. In Spain, Gutiérrez (1996), Benito et al. (1998, 2000), Gutiérrez and Gutiérrez (1998), and Gutiérrez et al. (2001) attributed as much as 200 m of local subsidence of subhorizontal Neogene sediments and anomalous thickening and deformation of Quaternary terraces to dissolution of underlying evaporite. Butler et al. (1987), Huntoon (1988), and Goydas (1989), among many others, discuss evaporite-related collapse only as a side issue.

A few prior investigations described genetic relationships between incision and diapirism. For example, Huntoon (1982) reported a diapiric anticline on the western edge of the Paradox basin whose axis follows the Colorado River as it winds through numerous meanders. These investigations support our conclusions that (1) evaporite tectonism is responsible for the regional collapse and anomalous local features in west-central Colorado that are described in this book, and (2) incision and lithostatic unloading triggers evaporite flow and anticlinal diapirism along the Eagle and Roaring Fork River valleys.

Current research

Since 1993, CGS geologists have mapped ten 7.5-minute quadrangles (Fig. 1) near and upstream of the confluence of the Roaring Fork and Colorado Rivers in the Carbondale and Eagle collapse centers (Kirkham et al., 1995, 1996, 1997a, 1998; Carroll et al., 1996; Kirkham and Widmann, 1997; Streufert et al., 1997a, 1997b, 1998; Streufert, 1999). The USGS mapped 11 1:24 000-scale quadrangles (Fig. 1) in the Eagle collapse center and in the northwest arm of the Carbondale collapse center that follows the Grand Hogback along the southwestern margin of the White River uplift (Scott and Shroba, 1997; Shroba and Scott, 1997, 2001; Lidke, 1998, 2002; Bryant et al., 1998; Scott et al., 2001, 2002; W.J. Perry, 2001, written commun., geologic map of Horse Mountain quadrangle; D.J. Lidke, 2001, written commun., geologic map of Edwards quadrangle; M.R. Hudson, 2001, written commun., geologic map of Gypsum quadrangle).

Kirkham and Streufert (1996) proposed that regional, late Cenozoic structural collapse in west-central Colorado could be due to flow and dissolution of evaporite. Kirkham and Widmann (1997) named the Carbondale collapse center and provided evidence that collapse is active. Widmann (1997) reported on deformation in the Eagle collapse center. Subsequent work by Kirkham et al. (1997b; 2001b), Kunk et al. (1997), and Kirkham and Streufert (1998a, 1998b) presented data on various aspects of the Carbondale collapse center. Bryant et al. (1998) confirmed that evaporite dissolution and collapse caused tight synclinal sagging of a young Tertiary conglomerate and recognized that flow of evaporite caused the collapse of overlying red beds along the northwestern part of the Carbondale collapse center. Lidke (1998) showed that at least 0.4 km and perhaps >1 km of collapse affected basaltic rocks in the Wolcott area of the Eagle collapse center. Scott et al. (1998, 1999) described evidence of regional collapse in the Eagle collapse center and the northwest part of the Carbondale collapse center and summarized the evaporite collapse model.

GEOLOGIC SETTING

Synopsis

The geologic history of west-central Colorado is complex. Bedrock units exposed in west-central Colorado include Proterozoic through Quaternary rocks; locally nearly 9 km of Phanerozoic strata exist (Figs. 3 and 4). Although lower Paleozoic rock stratigraphy is relatively simple, the late Paleozoic Ancestral Rocky Mountain and Late Cretaceous–early Tertiary Laramide orogenic events created more complex relationships. The Central Colorado trough, a northwest-trending basin that formed between the Ancestral Front Range and Uncompahgre uplifts (Fig. 1), amassed thick sequences of Pennsylvanian marine facies, including the evaporite responsible for the collapse. Closer to the uplifts, thick sequences of coarse-grained Pennsylvanian and Permian arkosic sediments, mostly of continental origin, first interfingered with trough facies and eventually covered them. More uniform Mesozoic strata then blanketed the region, including the adjacent former highlands. Laramide tectonism deformed these older rocks and also syntectonic sedimentary rocks that filled basins adjacent to Laramide uplifts. Although the greatest volume of basaltic lavas erupted between latest Oligocene time (ca. 25 Ma) and late Miocene time (ca. 10 Ma), smaller quantities continued to erupt during the remainder of the Miocene, Pliocene, and Quaternary. Lava flows and lapilli tuff erupted during the latest volcanic event ca. 4 ka at Dotsero.

Precambrian through Mesozoic time

In Early and Middle Proterozoic time, accretion of magmatic arcs and interarc basins from 1.8 to 1.65 Ga and magmatism from 1.7 to 1.0 Ga built Colorado's continental crust on the southern edge of the growing continent (Reed et al., 1987, 1993). Uplift and deep erosion removed several kilometers of Proterozoic rock and formed a profound erosional unconformity that truncated Proterozoic metamorphic and magmatic rocks prior to the Paleozoic. Relatively thin, intermittent continental shelf deposition covered west-central Colorado with clastic and carbonate rocks from Late Cambrian through Early Mississippian time (Fig. 4).

Major elongate uplifts known as the Ancestral Rocky Mountains began to form in Early or Middle Pennsylvanian

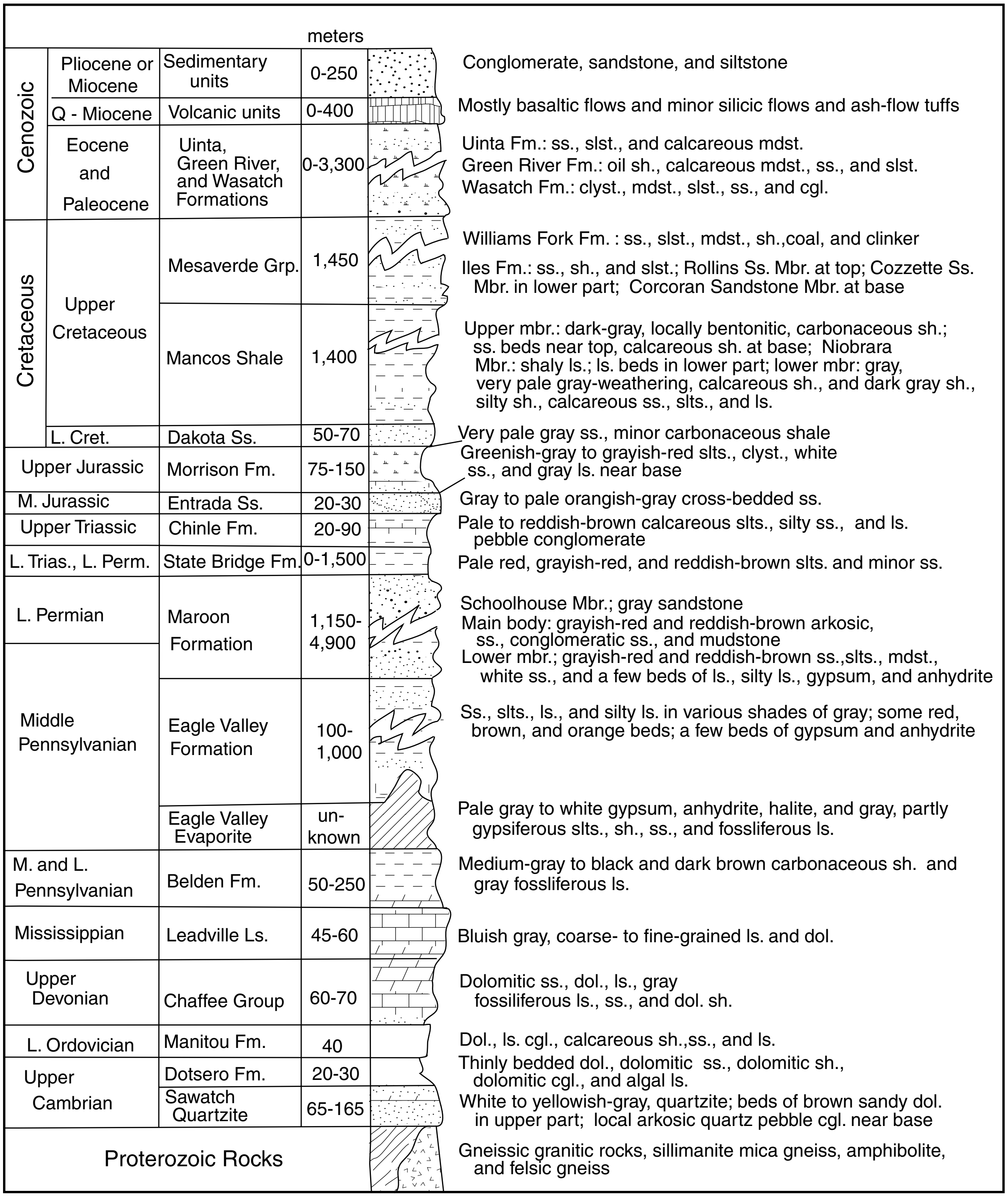

Figure 3. Generalized stratigraphic relations in west-central Colorado. Adapted from Tweto and Lovering (1977), Johnson et al. (1990), Kirkham et al. (1997a), Scott and Shroba (1997), Bryant et al. (1998), Lidke (1998, 2002), Scott et al. (1999), Shroba and Scott (1997, 2001), Scott et al. (2001), and Scott et al. (2002).

time (Waechter and Johnson, 1986; Ye et al., 1996; Kluth, 1998). These mountains included the Ancestral Uncompahgre and Ancestral Front Range uplifts (Fig. 1), where Proterozoic and lower Paleozoic and rocks were exposed. The uplifts became sources for proximal facies of coarse arkosic debris that ringed the intervening Central Colorado trough. Distal facies of fine-grained clastic, carbonate, and evaporite deposits filled the central parts of the trough (Mallory, 1971; De Voto et al., 1986). Halite, gypsum, anhydrite, and gypsiferous siltstone, which comprise much of the Desmoinesian Eagle Valley Evaporite, accumulated within the Central Colorado trough. Original depositional thickness of the evaporite is poorly constrained due

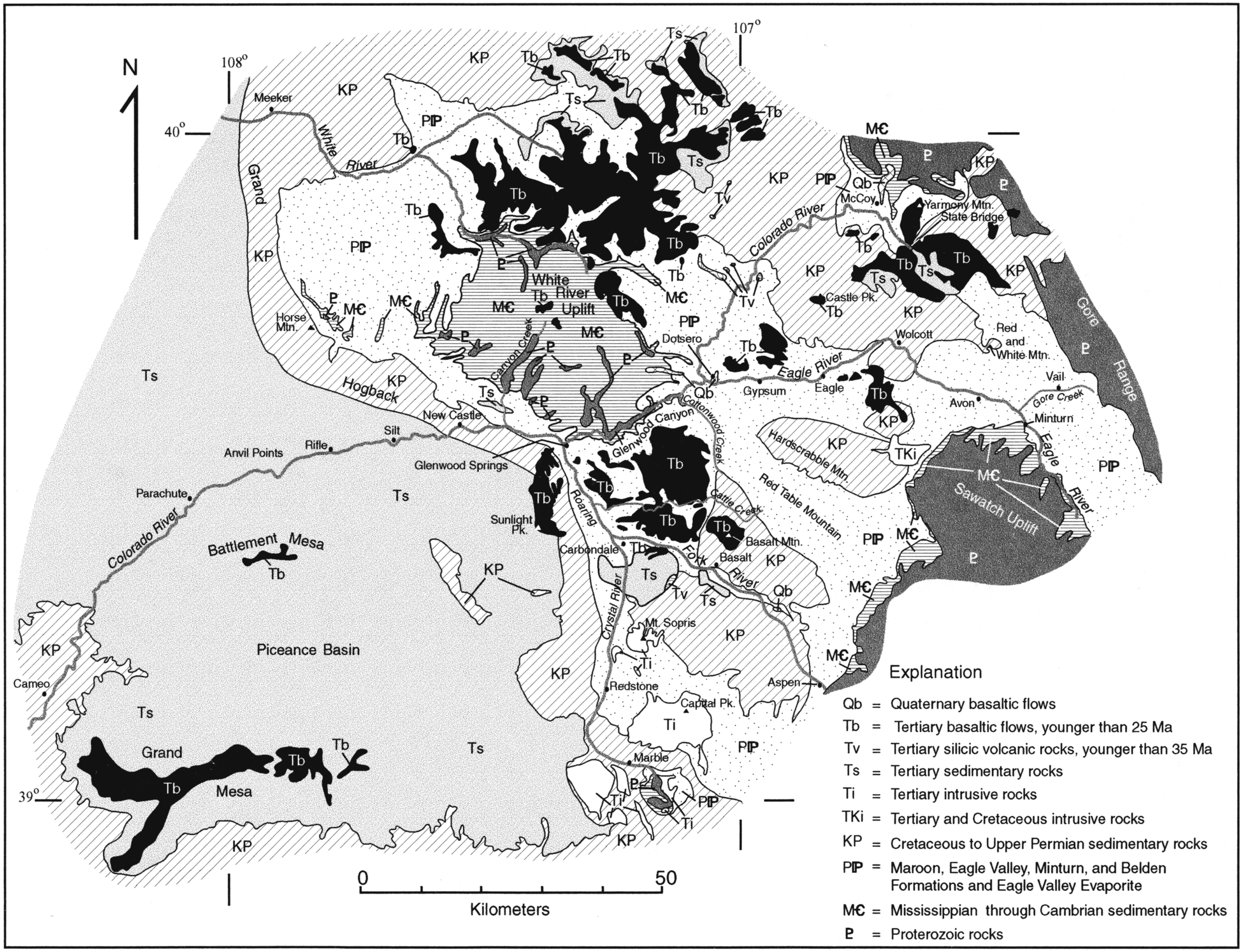

Figure 4. Generalized geologic map of west-central Colorado. Adapted from Tweto (1979).

to postdepositional flow. Intrabasin flow probably affected the original depositional geometry of the evaporite even as they were being deposited, and the dense, uneven overburden of Pennsylvanian and Permian arkosic red beds probably further induced evaporite deformation (Tweto, 1977; Freeman, 1971; De Voto et al., 1986). Permian, Triassic, and Jurassic fluvial, eolian, and lacustrine deposits record the gradual erosion and submergence of the Ancestral Rocky Mountain uplifts. A thick sequence of intertonguing Cretaceous marine and continental rocks later covered west-central Colorado (Fig. 4).

Late Cretaceous and Cenozoic time

Laramide crustal deformation, which included regional uplift, local uplift, and development of adjacent depositional basins, occurred in the Rocky Mountains and Colorado Plateau during Late Cretaceous to early Tertiary time (Tweto, 1977). Magmatism accompanied the Laramide tectonism. The basins collected debris east, west, and within the complex of uplifts of the Laramide Rocky Mountains. The late Laramide Grand Hogback monocline (Tweto, 1975) is a major basement structure with >6 km of structural relief that separates the White River uplift from the Piceance basin (Fig. 4). Laramide deformation must have reactivated flow and dissolution of the evaporite, particularly where subsequent erosion stripped most of the lower Paleozoic strata from the White River uplift. Over 3 km of Paleocene and Eocene sediments accumulated in the Piceance basin during the Laramide (Figs. 3 and 4).

The Oligocene granitic Mount Sopris pluton (Fig. 4), the northernmost of several late Eocene to Oligocene plutons in and near the Elk Range, intruded near the southern margin of the Carbondale collapse center (Streufert, 1999). A remnant of an ash-flow tuff preserved on the northeast side of Mount Sopris was erupted during this period of igneous activity.

Extensional tectonism began in the Rio Grande rift during the middle Cenozoic and continued into the Holocene (Fig. 1). Widespread basaltic volcanism, bimodal basaltic-rhyolitic volcanism, and granitic plutonism affected the southern Rocky Mountains during this same time (Lipman and Mehnert, 1975; Larson et al., 1975; Tweto, 1977). Also, the region north of the San Luis basin of the Rio Grande rift underwent extensional tectonism expressed by the right-stepping, late Cenozoic upper Arkansas River and Blue River basins (Fig. 1) and by north- to northwest-trending normal faults in areas adjacent to these basins (Tweto, 1979). Large areas in west-central Colorado were partially covered with basaltic flows from numerous eruptive centers extending from Grand Mesa to the White River uplift and to the Gore Range during the late Cenozoic (Larson et al., 1975; Budahn et al., this volume).

Until ca. 9 or 10 Ma, widespread basaltic lavas flowed onto an erosion surface with relatively low relief, locally creating stacks of progressively younger flows. At present, outside the areas of collapse, the base of these basaltic flows stands at elevations between ~2.9 and 3.4 km and is 1.4–2.0 km above modern valleys (T.A. Steven, USGS emeritus, 1997, personal commun.). Based on these observations, we hypothesized that (1) the base of preserved remnants of these late Oligocene to Miocene volcanic flows could be used as a regional datum, and (2) volcanic rocks found at lower elevations within areas of collapse could be used to quantify the amount and timing of collapse (Kirkham et al., 1997b; Scott et al., 1998, 1999).

The ancestral Colorado River system was established in the region sometime during the Miocene. Incision rates in the Miocene, although not well constrained, appear to be relatively low, whereas the rates greatly increased ca. 3 Ma (Kirkham and White, 2000; Kirkham et al., 2001a). Several papers in Young and Spamm (2001) and Steven (this volume) support this increased Pliocene incision rate. Late Miocene (7.7–7.8 Ma), Pliocene (3–4 Ma), and Quaternary volcanic rocks were episodically erupted onto the continually eroding and evolving landscape. As the rivers eroded rock from the valleys, lithostatic loads on underlying evaporite strata decreased and evaporite flow toward river valleys occurred.

The cumulative effects of these multiple periods of deformation have thoroughly deformed the original evaporite sequences in most areas. Therefore, the original distribution and thickness of evaporite are unknown. Mallory (1971) and De Voto et al. (1986) estimated that the Eagle Valley Evaporite is presently as much as 2.7 km thick in both the Carbondale and Eagle areas, and Mallory attributed this great thickness to local diapirism.

CORRELATION OF LATE CENOZOIC BASALTIC FLOWS

During this study, investigators mapped and determined age, geochemical, and petrographic data for late Cenozoic basaltic lava flows, minor silicic tuffs, and eruptive centers. These data were used to interpret and measure structures in collapsed areas and to relate magma genesis to regional tectonic events. These flows were sampled extensively both from within and adjacent to the Carbondale and Eagle collapse centers and from Grand Mesa and the White River uplift.

Over 130 $^{40}Ar/^{39}Ar$ dates ranging from 0.3 to 35.2 Ma were obtained from samples of volcanic rocks (Kunk and Snee, 1998; Kunk et al., 2001; Kunk et al., this volume). Over 220 basaltic samples were analyzed by Unruh et al. (2001) and Budahn et al. (this volume) for major elements (XRF methods), minor elements (XRF and INAA methods), and trace elements (INAA methods). A select group of samples were also analyzed for Pb, Sr, and Nd isotopes. Phenocryst modes for 50 thin sections and aphyric groundmass modes for 17 thin sections of basaltic rocks were also determined. In spite of obvious crustal contamination, Budahn et al. (this volume) recognized eight major chemical groups among the samples by using plots of Hf/Ta and La/Y ratios. Variations in abundances of Rb, Sr, Ba, Th, and U define as many as eight subdivisions within each of these major groups, and further subdivisions are based on distinctive isotopic signatures, resulting in a total of 44 geochemical rock groups. A comparison of trace-element data (Budahn et al., this volume) with petrographic modal analyses indicates a close correspondence between minor differences in modal phenocryst abundances and trace-element groupings in basaltic flows. Even mineralogical differences as small as 5% and 2% modal olivine correlate with distinct chemical subdivisions.

Hudson et al. (this volume) used paleomagnetic data from 57 sites to correlate between Miocene basaltic flows, to distinguish between flow emplacement attitudes and structural tilt attitudes, and to provide data for correlation of flows within collapsed areas and on Grand Mesa outside the collapsed areas. Their study of basaltic flows in collapse centers indicates that the dips of flows resulted from deformation rather than original emplacement. In some highly deformed flows, paleomagnetic data indicate 30° to 100° (overturned) tilts, amounts that are more accurate than the approximate dips discernible from field relationships.

We conclude from field relations and these geochemical, geochronological, and paleomagnetic data that many basaltic vents, each with its own distinct lava composition, erupted between 24 and 10 Ma and nearly covered a low-relief erosion surface in west-central Colorado. The surface was carved into Tertiary, Mesozoic, and Paleozoic strata deformed by the Laramide orogeny. Outside obviously collapsed areas, these flows are now at elevations of 2.9–3.4 km. Within collapse areas, they are as low as 2.1 km. Before collapse, this postulated low-relief surface with widespread basaltic cover extended from Grand Mesa to the east side of the Eagle collapse center.

Basaltic flows and debris eroded from them are absent in areas such as Hardscrabble Mountain and Porphyry Mountain in the Eagle collapse center (Lidke et al., this volume), and from the northwest arm of the Carbondale collapse center along the southwest flank of the White River uplift (Scott et al., this volume). This suggests that parts of the low-relief surface may never have had a basalt cap. Much of the Carbondale collapse center between Basalt Mountain and Glenwood Springs and the Eagle collapse center between Gypsum, Yarmony Mountain, and Avon had extensive areas mantled by basaltic rocks. Grand Mesa and much of the White River uplift also were covered with thick basaltic flows. Widespread remnants of basalt-rich surficial deposits (Carroll et al., 1996; Madole, 1999, 2001) cover areas east of Battlement Mesa, suggesting that basaltic flows were once abundant there. Thus, the basaltic lava field was widespread across the erosion surface but not continuous.

CONCEPTUAL MODEL FOR LATE CENOZOIC EVAPORITE TECTONISM

A broad low-relief erosion surface characterized the region from Grand Mesa to the Gore Range 25 Ma. The maximum relief on the erosion surface was ~500 m. Between ca. 25 and 10 Ma, basaltic lavas erupted onto the erosion surface, locally creating stacked sequences of progressively younger flows. Incision of rivers through this basalt-mantled erosion surface after ca. 10 Ma is the triggering mechanism for widespread, large-scale, late Cenozoic evaporite tectonism in west-central Colorado. As rivers incised to progressively greater depths, overburden was removed and lithostatic loads on evaporite under river valleys was reduced relative to evaporite under highlands. This differential lithostatic load promoted lateral flow of evaporite from under highlands toward river valleys. Withdrawal of evaporite from beneath the highlands induced collapse. Upward flow of evaporite beneath river valleys formed evaporite-cored valley anticlines and local diapirs, analogous to the Meanders anticline of the Colorado River in Utah (Huntoon, 1982).

Dissolution of evaporite minerals created void space that induced collapse of overlying strata, locally creating topographic depressions in which syn-collapse sediments accumulated. As these processes of flow and dissolution continued, basaltic flows gradually collapsed to lower elevations. There is no known evidence that evaporite flow blocked rivers or streams, therefore dissolution and collapse rates equaled or exceeded the rates at which evaporite flowed upward.

RELATIONSHIPS WITH SURFACE WATER AND GROUNDWATER

Where pathways of relatively fresh groundwater intersect evaporite bodies, highly to moderately soluble minerals such as halite, gypsum, and anhydrite are dissolved, adding sodium, chloride, calcium, and sulfate ions to the groundwater and creating void space in the evaporite. Although large quantities of groundwater circulate beneath valleys and concentrate dissolution there, dissolution also affects highlands, as documented by sinkholes and saline well water. These saline groundwaters discharge to the surface-water system as thermal springs and as seepage into alluvial aquifers (Kirkham et al., 1999), increasing salt loads to rivers that cross collapse areas.

Hot springs in the area, such as Yampah and Dotsero hot springs, discharge large volumes of dissolved halite and gypsum into the surface-water system (URS Corporation, 1981; Eisenhauer, 1986). Yampah hot spring, which supplies the water for the Glenwood Hot Springs Pool, discharges ~240 metric tons of dissolved halite and gypsum each day (Barrett and Pearl, 1976). The amount of dissolved halite and gypsum from this single hot spring is roughly equivalent to the creation of one new sinkhole with a volume of ~108 m^3 per day, assuming a specific gravity of 2.23 g/cm^3 Geothermal heat in the groundwater system greatly increases the solubility of evaporite, which probably explains the anomalously high salt concentrations in thermal springs. The combined surface discharge of all the hot springs near Glenwood Springs and Dotsero and the associated saline groundwater that seeps directly into the alluvial aquifer contributes an estimated 0.4 million metric tons of dissolved solids to the Colorado River annually (Eisenhauer, 1986).

Upstream of the Eagle and Carbondale collapse centers, the Colorado, Eagle, and Roaring Fork Rivers have relatively low dissolved-solid loads (Warner et al., 1984; Bauch and Spahr, 1998). The dissolved-solid loads in the Colorado and Eagle Rivers significantly increases as the rivers cross the Eagle collapse center (Bauch and Spahr, 1998). The dissolved-solid load in the Roaring Fork River increases by a factor of four as it crosses the Carbondale collapse center (Warner et al., 1984). During a 24-year period of monitoring by the USGS National Water-Quality Assessment Program, the Colorado River downstream from the collapse centers (at Cameo near Grand Junction) carried an annual mean dissolved-solids load of ~1.36 million metric tons (Bauch and Spahr, 1998). Chafin and Butler (this volume) estimate that ~0.8 million metric tons of evaporite minerals are dissolved and removed by the Colorado River from the collapsed areas each year. The rivers are ultimately responsible for transport and removal of dissolved evaporite from the collapse areas.

LATE CENOZOIC RIVER INCISION AND REGIONAL UPLIFT

Sometime between ca. 20 and 7.8 Ma, an ancient river, probably the ancestral Colorado River, eroded a broad valley ~0.4 km deep into the southern flank of the White River uplift (Kirkham et al., 2001a; Kunk et al., this volume). Available data do not constrain the timing of this incision well. The broad paleovalley was adjacent to and south of modern Glenwood Canyon at 7.8 Ma. Subsequent eruptions of 7.7 to 7.8 Ma basaltic flows filled the paleovalley, which caused the river to cut a new channel around the north side of the lava-filled paleovalley and initiated the cutting of Glenwood Canyon. Between 7.8 and 3.0 Ma, the rate of river incision in Glenwood Canyon averaged ~0.024 m/k.y. (m/1000 yr). During the last 3 m.y. the rate increased by an order of magnitude to 0.24 m/k.y., and over half the entire 1270-m-deep canyon was carved (Kirkham et al., 2001a). Rates at two sites on tributaries to the Colorado River independently support this high post-3 Ma incision rate. Larson et al. (1975) reported a rate of 0.26 m/k.y. based on the height of 1.5 Ma basaltic flows from Triangle Peak above the Roaring Fork River between Aspen and Basalt. Dating by Kunk et al. (2001) confirmed this rate. Larson et al. (1975), using K-Ar dating, also determined an incision rate of 0.24 m/k.y. using a 0.64 Ma basaltic flow on a tributary of the Colorado River near State Bridge. Significant parts of the Carbondale collapse center also have evidence of major collapse during the last 3 m.y. (Kirkham et al., this volume), which supports the high incision rate.

Steven (this volume) concludes that late Cenozoic uplift in the Rocky Mountain region increased rates of incision and triggered late Cenozoic evaporite tectonism in west-central Colorado. Other factors that may have affected incision rates include changes in base level, such as those described in the lower Colorado River system (Young and Spamm, 2001) and climate. Nearby uplifts with strong evidence of late Cenozoic activity include the Gore Range to the east (Naeser et al., this volume) and the San Juan Mountains to the south (Steven et al., 1995). Other adjacent uplifts, such as the Sawatch uplift to the southeast, Uncompahgre uplift to the west, and Front Range to the east, are suspected of late Cenozoic movement (Steven, this volume; Steven et al., 1997). The White River uplift, which lies north and west of the collapse areas, underwent differential late Cenozoic uplift relative to a basin on its northern flank. McMillan et al. (2002) described evidence of late Cenozoic uplift in both Wyoming and northern Colorado. Steven (this volume) also finds that the increased rate of incision during the last 3 m.y. is correlative with the most prominent periods of uplift.

AREA AND VOLUME OF COLLAPSE

We base our estimates of the areas affected by evaporite-related collapse and the volume of collapse primarily on interpretations of (1) field relationships established by published 1:24 000-scale geologic mapping, (2) seismic reflection profiles (Perry et al., this volume), (3) data from a few drill holes, (4) unpublished reconnaissance and detailed mapping by the USGS and CGS, and (5) map relations depicted by Tweto et al. (1978). The area of the Carbondale collapse center covers ~1200 km^2, and the area of the Eagle collapse center is nearly 2500 km^2 (Figs. 2 and 5). An area of ~8 km^2 at Castle Peak in the middle of the Eagle collapse center probably escaped collapse, because the elevations of Miocene flows there are similar to those of flows outside of the collapse areas.

Three areas with equivocal evidence of collapse are adjacent to the better established areas of collapse (Fig. 2). The Eagle Valley Evaporite either currently underlies these areas, or it was present there during the late Cenozoic but has since been removed by erosion or dissolution. North of the Eagle collapse center, an area of ~360 km^2 is suspected of collapse. Interpreted seismic reflection data indicate that relatively small normal faults cut upper Paleozoic strata that overlie the Eagle Valley Evaporite, but they do not cut the Mississippian Leadville Limestone that underlies the evaporite (Larry Moyer, geological consultant, 2000, written commun.). An area of ~320 km^2 west of the Eagle collapse center and north of the Carbondale collapse center was formerly underlain by evaporite during the late Cenozoic; possible, but unproven late Cenozoic collapse may have occurred here prior to erosion and dissolution of the evaporite. A third area of nearly 700 km^2 that lies south of both the Eagle and Carbondale collapse centers also may have undergone late Cenozoic collapse. The Eagle Valley Evaporite locally crops out along the Roaring Fork River in this area. Irregular swarms of faults that cut strata overlying the evaporite on the west side of the river are suggestive of evaporite deformation, but late Cenozoic activity has not been documented on these structures.

Volumes of known and suspected areas of collapse within the Eagle collapse center and most of the Carbondale center are calculated using the estimated vertical collapse from the assumed basaltic datum. Structure contours were drawn on the base of the basaltic rocks where they are preserved and extrapolated or interpolated into collapsed areas lacking basalt (Fig.

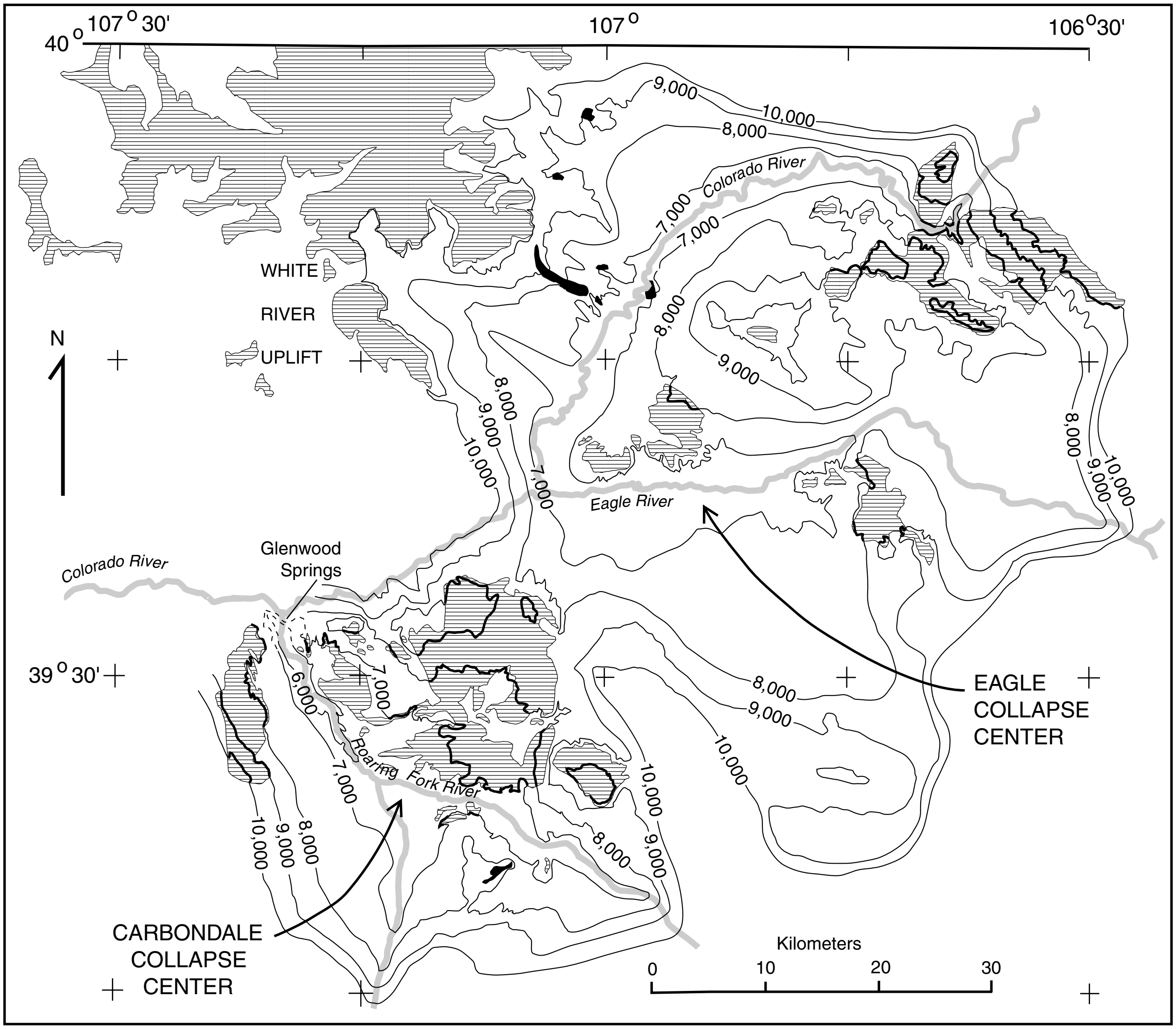

Figure 5. Structure contours drawn on the base of 10 to 24 Ma volcanic rocks. Bold contour lines are used where basaltic rocks are present, and thinner contour lines extrapolate beyond control by outcrops. Areas of basaltic lava flows are darkly shaded and silicic ash-flow tuffs and lava flows are lightly shaded; both are adapted from Tweto (1979). The contours are in thousands of feet and are based on topographic and geologic maps that use English units.

5). The collapse volume for each contour interval within known areas of collapse was calculated by averaging the areas encompassed within adjacent 1000-foot contours and by multiplying this averaged area by the contour interval (1000 feet). These contour interval volumes were summed from the 10000-foot contour to the present river levels to obtain a total collapse volume of ~2300 km^3. We conclude that this volume of evaporite was removed by dissolution from the collapse centers and carried down the Colorado River during the late Cenozoic. At the estimated modern dissolution rate of 0.8 million metric tons annually, it would take 6.4 m.y. to dissolve the estimated 2300 km^3 that has been removed from the collapsed area, assuming a specific gravity of 2.23 g/cm^3 for the evaporite. The annual rate of evaporite removal probably varied widely over geologic time, and our estimate of the collapse area volume is approximate. But this calculation demonstrates that evaporite dissolution can account for the structural lowering of the basaltic rocks.

SUMMARY

Geologic mapping, supported by topical studies focused on correlation, dating, and structural analysis of late Cenozoic volcanic rocks, has led to the discovery of widespread late Cenozoic collapse in west-central Colorado. Flow and dissolution of halite, gypsum, and anhydrite in the Pennsylvanian Eagle Valley Evaporite caused the collapse. The area affected by late Cenozoic collapse covers at least 3600 km^2. Strata are lowered as much as 1.2 km in collapsed areas, and dissolution removed an estimated 2300 km^3 of evaporite from collapsed areas during the late Cenozoic. Flow, mostly by recrystallization, played a major role in the process and probably began soon after burial of evaporite by differential loads of denser clastic deposits. Late Cenozoic river incision triggered the most recent episode of evaporite flow. As rivers incised deeply into strata overlying evaporite deposits, the differential lithostatic loads promoted evaporite flow. Evaporite flow continued episodically to the Quaternary and probably to the present.

To facilitate regional collapse, evaporite must be removed from the area. In upland regions, both withdrawal of evaporite by flow and dissolution contribute to collapse. Dissolution effectively removes evaporite from beneath river valleys where large volumes of relatively fresh groundwater circulate. Flow brings additional evaporite to the valleys, where the evaporite moves upward to become diapiric at least locally. Dissolution and collapse rates in the valleys must equal or exceed rates at which evaporite flows upward, because there is no evidence that evaporite blocked the rivers.

Saline groundwater discharges to the surface-water system through thermal springs and by subsurface seepage into alluvial aquifers. The Colorado River and its tributaries transport the dissolved salts out of the region and provide the ultimate evaporite removal system. Accelerated river incision during the past 3 m.y. increased evaporite flow and probably enhanced dissolution. Historic sinkholes and high salinity loads in rivers and thermal springs indicate that dissolution and collapse are still active in west-central Colorado.

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