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Eagle collapse center: Interpretation of evidence for late Cenozoic evaporite-related deformation in the Eagle River basin, Colorado

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ABSTRACT

Evaporite tectonism resulted in deformation and collapse over an area of ~2500 km^2 that is referred to as the Eagle collapse center. The collapse center includes much of the Eagle and Colorado River drainage basins between Vail, Dotsero, and McCoy, Colorado. The volume loss of evaporitic rocks by dissolution in the collapse center is estimated to be nearly 1700 km^3. Before ca. 10 Ma, Miocene basaltic flows partly covered an extensive, nearly horizontal, low-relief surface. Parts of this surface collapsed >1.3 km near the present-day Eagle and Colorado Rivers. Remnants of this surface outside the area of collapse, such as highlands of the White River uplift, the flank of the Gore Range, and Basalt Mountain, stand at elevations of 2.9–3.6 km. The high-standing Castle Peak basaltic cap, situated near the center of the Eagle collapse center, may not have collapsed, or collapsed little. The areas of collapse lie within or nearby known and inferred limits of the Pennsylvanian Eagle Valley Evaporite (mostly halite, gypsum, and anhydrite) that was deposited in the Central Colorado trough. Our geologic mapping and research in the Eagle collapse center delineate synclinal sags in the basaltic flows with amplitudes of 0.5–1 km, sinuous and discontinuous high-angle faults that cut basaltic flows, elongate grabens, evaporite-cored anticlines, and an ellipsoidal fault system that drops a 30 km × 10 km mountain block of younger strata into evaporite. Collapse as far as 20 km from the Colorado and Eagle Rivers suggests that the greater load on evaporite beneath surrounding highlands causes lateral flow of evaporite toward anti-

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clinal crests in river valleys. Thus, gravity-driven evaporite flow and removal of evaporite by dissolution in groundwater and by subsequent discharge to surface waters combine to produce large-scale collapse. Although most evaporite tectonism post dates the basaltic flow capped surface, local angular unconformities under this surface record earlier, possibly Laramide evaporite tectonism, and overthickened post-evaporite red beds record some late Paleozoic evaporite deformation.

INTRODUCTION

For nearly a half century, evidence of evaporite tectonism has been recognized in western Colorado. Within the drainage basin of the Eagle River (Fig. 1), Hubert (1954) assigned some 300 m of relief on Tertiary basaltic flows near Eagle to "adjustment of the underlying gypsum," and Wanek (1953) recognized 900 m of synclinal subsidence of Tertiary basaltic flows near State Bridge. Benson and Bass (1955) reported a young diapiric salt anticline along the Eagle River that tilted Tertiary basaltic flows near Gypsum. Tweto (1977) called for voluminous flow of evaporite that began soon after denser Pennsyl-

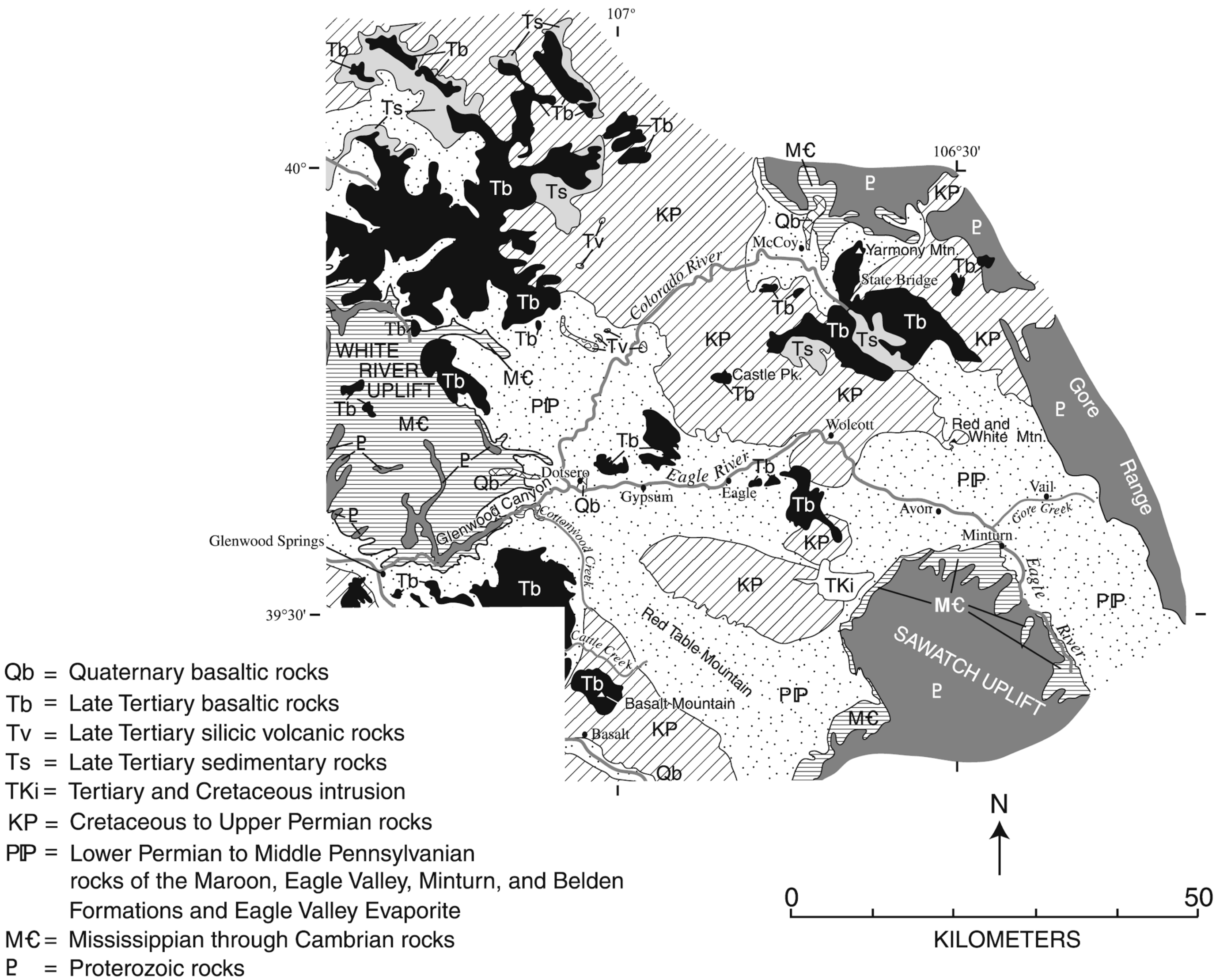

Figure 1. Map showing generalized geology and major topographic features of the Eagle collapse area (modified from Figure 4 of Kirkham and Scott, this volume, and after Tweto, 1979).

vanian and Permian arkosic sediments covered the evaporite. He also attributed young geomorphic features near the Eagle River to evaporite tectonics.

This chapter explores relations of Pennsylvanian evaporite to younger Paleozoic and Mesozoic strata and Tertiary volcanic rocks in a region centered near the town of Eagle in western Colorado (Fig. 1), a region drained by the deeply incised Eagle and Colorado Rivers. Large parts of the Eagle River basin and smaller parts of the Colorado River basin are included in this region, referred to here, and in Scott et al. (1998, 1999), as the Eagle collapse center (Fig. 2). The area of the collapse center is underlain in part by the Pennsylvanian Eagle Valley Evaporite and shows evidence for evaporite tectonism, some of which is late Cenozoic in age. As indicated in Figure 2, however, the extent of this area affected by evaporite-related deformation is imprecisely known. Previous research in this region led to recognition of the processes of evaporite upwelling, dissolution, and collapse. Our documentation and interpretation of evidence for widespread late Cenozoic, evaporite tectonism, dissolution, and collapse emphasizes the regional aspects of this evaporite-related deformation. This chapter expands on, and refines, some data and conclusions presented in Scott et al. (1998, 1999).

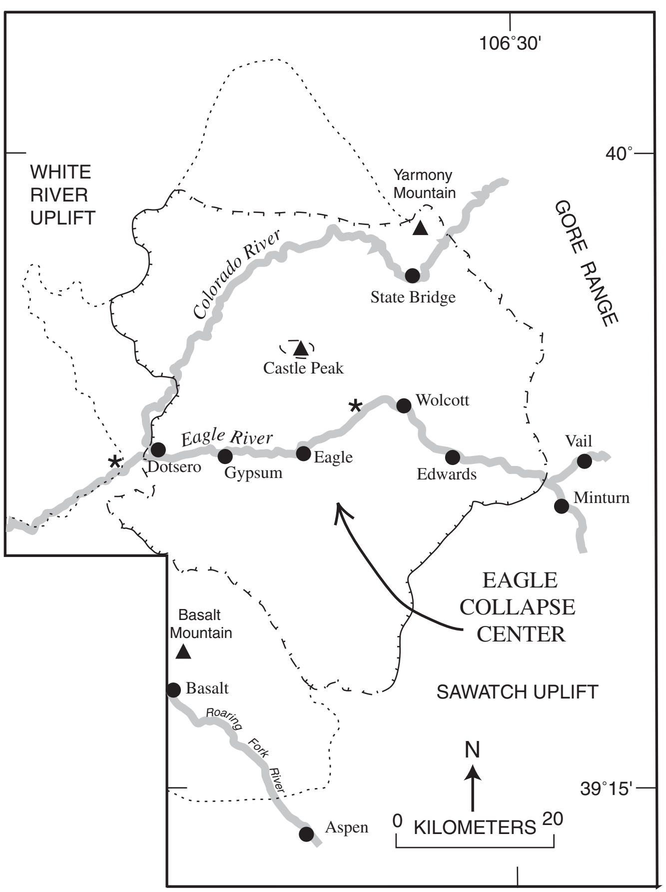

Figure 2. Sketch map showing area of collapse in the Eagle collapse center (modified from Figure 2 of Kirkham and Scott, this volume). Dashed lines indicate uncertain boundaries of collapse center; dotted boundaries of areas northwest of State Bridge and west and southwest of Dotsero, are possible edges of collapse center, but include areas less likely to have experienced collapse. Two large, asterisk symbols mark approximate locations of volcanic ash deposits (see last section of text)

The introductory chapter of this volume (Kirkham and Scott, this volume) discusses evidence for a basaltic datum defined by 10–24 Ma basaltic flows that covered parts of an extensive low-relief surface over a large region that includes the Eagle and Carbondale collapse centers. In that chapter they also discuss late Cenozoic rates of incision that in part triggered and controlled late Cenozoic evaporite-related deformation. Evidence for late Cenozoic evaporite deformation and its resulting modification of the datum attached to the flows in the Eagle collapse center is discussed in more detail in this chapter.

GEOLOGIC SETTING

In a synthesis of late Paleozoic stratigraphy and syndepositional tectonism, De Voto et al. (1986) described the depositional setting and the present-day thicknesses of evaporite and related sediments that accumulated in the Pennsylvanian and Permian Central Colorado trough. However, abundant evidence of evaporite tectonism indicates that these thicknesses probably represent deformed thicknesses rather than depositional thicknesses. The trough extended from the ancestral Front Range, which essentially coincides with the western margin of the present-day Gore Range on the east side, to the eastern edge of the ancestral Uncompahgre uplift on the west side (Fig. 1 of Kirkham and Scott, this volume). Kluth (1986, 1998) concluded that the Central Colorado trough, and other Pennsylvanian and Permian basins in Colorado and neighboring states, formed between intracratonic block uplifts that were related to the collision and suturing of North America with South America and Africa, during the Ouachita-Marathon orogeny. Ye et al. (1996, 1998) pointed out that reverse faults bound some of these late Paleozoic intermountain basins; they attributed formation of the basins and bounding uplifts to northeast-directed compression related to subduction along an imprecisely defined southwestern margin of the late Paleozoic, North American continent. De Voto et al. (1986) estimated that there is as much as 2.5 km of halite, gypsum, and anhydrite in two parts of the Central Colorado trough, one around Carbondale and the other around Eagle, but Murray (1966) attributed some of these great thicknesses to diapiric structures. Schenk (1989) recognized six cycles of evaporite deposits in the Eagle basin part of the Central Colorado trough, and concluded that the cycles represent sea-level changes modulated by accumulation and ablation of Gondwanan ice centers. After deposition of the Middle Pennsylvanian evaporite-bearing sequence and the overlying Upper Pennsylvanian to Lower Triassic arkosic strata in the Central Colorado trough, the region was covered by ~2.9–4.7 km of Mesozoic sediment (Kirkham and Scott, this volume).

Superimposed on the Paleozoic and Mesozoic stratigraphic framework of this region are Late Cretaceous to Eocene compressional structures of the Laramide orogeny, which in part reactivated earlier Precambrian and Paleozoic structures (Tweto, 1975). During the Laramide orogeny, reverse slip along the Gore fault accompanied uplift of the Gore Range (Tweto, 1975; Kellogg, 1999) and the Gore fault borders the east side of the Eagle collapse area. Similarly, the Sawatch Range was uplifted during the Laramide orogeny (Tweto, 1975), and the uplift coincided with reverse slip along bounding faults of the range (Kellogg, 1999) and formation of the Sawatch anticline (Tweto, 1975). The axial trace of the Sawatch anticline approximately coincides with the crest of the range, and the fold plunges gently northward beneath the southeastern part of the Eagle collapse center. Along and near the west side of the collapse center, the White River uplift and the north- to northwest-trending Grand Hogback monocline formed late during the Laramide orogeny, probably in middle to late Eocene time (Tweto, 1975). The monocline probably is related to a blind thrust at depth (Perry et al., this volume). Many smaller Laramide folds and faults are present throughout the region.

The Laramide orogeny was followed by early to late Tertiary erosion of Laramide uplifts, deposition of Tertiary sediments, and volcanism. During early Tertiary time, sediment was deposited on the flanks of eroding Laramide highlands that were uplifted during the Laramide orogeny. During middle to late Tertiary time, ca. 25–10 Ma, basaltic flows erupted and covered significant parts of the collapse center and other regions of western Colorado (Larson et al., 1975). Between Dotsero and McCoy, ca. 19–20 Ma, several silicic volcanic centers erupted; at least one of these centers was the source of an ash-flow tuff in the western part of the collapse center, near Porphyry Mountain. By late Tertiary time, regional extension formed north- to northwest-trending normal faults (Tweto, 1975, 1979), many of which were superimposed on and, in part, reactivated earlier Laramide structures (Kellogg, 1999). After ca. 10 Ma, the rate of basaltic eruptions significantly decreased. The last eruption fed the small Dotsero flow near the junction of the Colorado and Eagle Rivers ca. 4 ka (Giegengack, 1962). The present rugged topography of the Rocky Mountains was created as broad regions of Colorado were uplifted and deeply eroded, beginning in late Miocene time (Steven et al., 1997; Steven, this volume). Local evidence for late Miocene uplift and incision is provided by a 7.8 Ma basaltic flow (Kunk et al., 1997; Kunk and Snee, 1998; Kirkham et al., 2002) where this flow overlies river gravels at a lower elevation than older basaltic flows and provides evidence for ~200 m of incision by the Colorado River ca. 20–7.8 Ma. (Streufert et al., 1997b; Kirkham et al., 1997, 2002, and this volume).

EVIDENCE FOR LATE CENOZOIC EVAPORITE DEFORMATION AND RELATED COLLAPSE

Several areas in the Eagle collapse center show evidence of late Cenozoic deformation. Deformed Miocene basaltic flows constrain the age of late Cenozoic structural features at these localities. Late Cenozoic basaltic flows are clearly deformed north of Gypsum, at several localities north and south of the Eagle River between Eagle and Wolcott, and southeast of State Bridge (Fig. 3). With the exception of the State Bridge area, the Eagle Valley Evaporite is known to underlie these deformed basaltic flows directly or at shallow depth. Near the southern margin of Eagle collapse center, the Eagle Valley Evaporite surrounds younger rock units that form Hardscrabble Mountain (Fig. 3). Field relations and seismic reflection data (Tweto, 1977; Perry et al., this volume) suggest that the Eagle Valley Evaporite flowed from beneath Hardscrabble Mountain, causing collapse of younger rock units that directly underlie the mountain. Collapse at Hardscrabble Mountain, and some other areas underlain by evaporite, probably began shortly after deposition of the evaporite in the Late Pennsylvanian or Permian (Mallory, 1971; Freeman, 1971). Some of the evaporite-related deformation at Hardscrabble Mountain, however, is Late Cretaceous or younger, because Upper Cretaceous rocks are deformed (Fig. 4, B–B′). Basaltic flows, which provide evidence of late Cenozoic deformation in other parts of the collapse center, are absent in the Hardscrabble Mountain area. Near Gypsum, Eagle, and Wolcott, relations of the Pennsylvanian evaporite to younger strata and basaltic flows suggest that some evaporite-related deformation may have occurred in Late Cretaceous or Paleogene time, prior to eruption of early Miocene basaltic flows.

Directly west of the Eagle collapse center, a sequence of relatively flat-lying basaltic flows (10–23 Ma) cap the White River uplift and lie at altitudes of ~2.9–3.6 km (Fig. 3). In the Eagle center, relatively flat-lying 22–23 Ma basaltic flows at Castle Peak (Kunk et al., this volume) lie at similar elevations (3.2–3.5 km), well above the 22–24 Ma basaltic flows at elevations that are as low as ~2.0 km in the collapse regions mentioned above. The cross sections shown in Figure 4 portray generalized structural and stratigraphic relations in several areas of the Eagle collapse center. These areas, as well as some areas not portrayed in these cross sections, are discussed below. Some of the discussions of individual areas refer to figures (6, 7, and 9) that are generalized from recent geologic maps of the Gypsum, Wolcott, and Eagle 7½′ quadrangles; the location of these quadrangle maps are shown in Figure 1 of the introductory chapter (Kirkham and Scott, this volume).

Castle Peak and Porphyry Mountain areas

At Castle Peak (Figs. 3 and 4), relatively flat-lying 22–23 Ma basaltic flows overlie Upper Cretaceous shale at elevations of ~3.2–3.5 km. Recent geologic mapping (Lidke, 2002) identified previously unmapped basaltic flows that cap a ridge ~2 km southeast of Castle Peak at elevations of ~3.0–3.5 km. The flows southeast of Castle Peak are interbedded with gravels and volcaniclastic lenses and probably are correlative with flows at Castle Peak; they are discussed in more detail in the section on the Eagle area. Basaltic flows at and nearby Castle Peak, are at

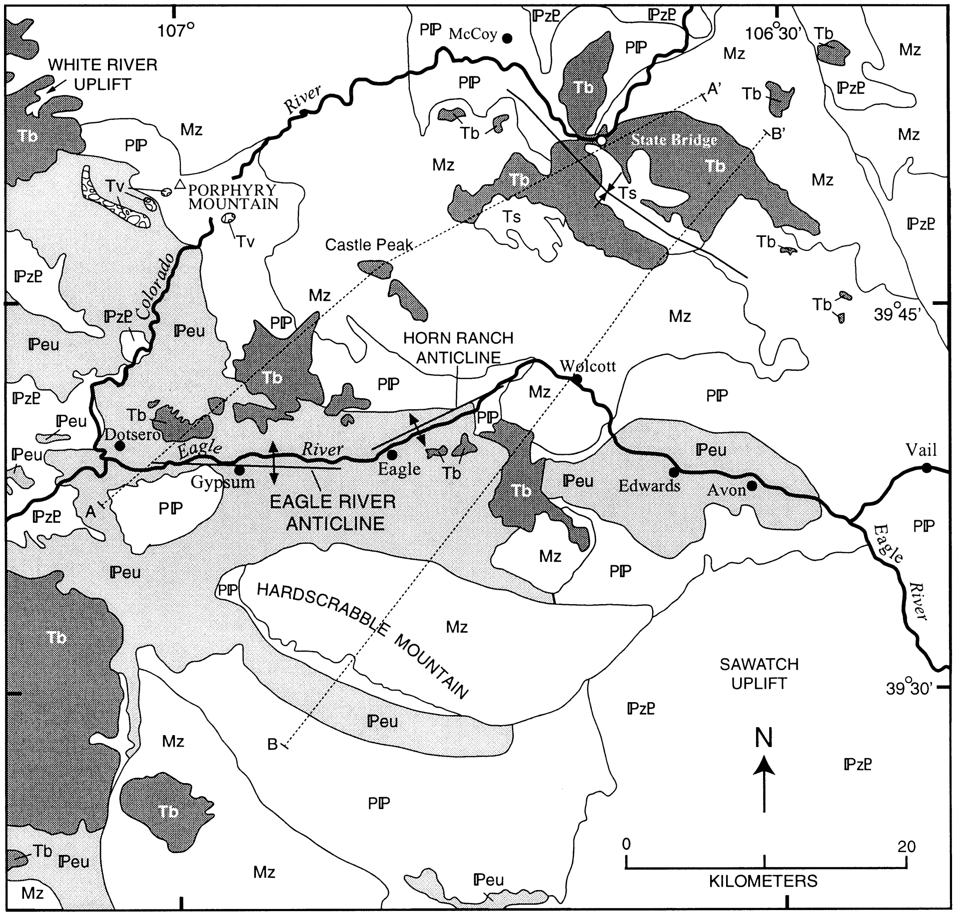

Figure 3. Generalized geologic sketch map of the Eagle collapse center (modified from Tweto et al., 1978). Ts—late Tertiary sediments; Tb—late Tertiary basaltic flows; Tv—late Tertiary ash-flow tuff; Mz—Mesozoic strata; ℙP—Permian and Pennsylvanian strata; ℙeu—Pennsylvanian Eagle Valley Formation and Eagle Valley Evaporite; PzP—Paleozoic and Precambrian rocks older than Eagle Valley Evaporite. Two evaporite-cored anticlines along the Eagle River are shown. Cross sections A–A′ and B–B′ are shown in Figure 4.

elevations similar to the regional basaltic datum that caps the White River uplift (Figs. 3 and 4), elevation ranges of 3.0–3.5 km and 2.9–3.6 km, respectively. However, basaltic flows are absent at Porphyry Mountain and probably were absent in much of the area between Castle Peak and the White River uplift, where a local topographic high may have existed during early Miocene emplacement of the basaltic flows. High-level flows preserved in the Castle Peak area may represent a remnant of the regional basaltic datum in the Eagle collapse center, which can be used to constrain the amount of collapse of early Miocene basaltic flows elsewhere in the Eagle center.

The absence of basaltic flows, combined with relations of early Miocene ash-flow tuff remnants and related siliceous intrusive rocks near Porphyry Mountain (Fig. 3), suggests that basaltic flows were not continuous between the White River uplift and the Castle Peak area. Ash-flow tuff and related intrusive rocks in the Porphyry Mountain area, which were previously studied by Riley (1949) and Shearer (1950), are exposed at elevations as low as ~2.1 km. Recent, unpublished mapping by Josette Stanley (University of Northern Colorado), and unpublished, reconnaissance mapping and isotopic dating by Robert Scott, Bruce Bryant, and Mick Kunk (U.S. Geological Survey) suggest that the tuffs and related intrusives are ca. 19–20 Ma (Kunk et al., this volume); this age is consistent with the Miocene age assigned to these units by Tweto et al. (1978). These unpublished studies also identified an ash-flow tuff along Poison Creek; there, the tuff is draped on 60-m-high valley walls of this small tributary of the Colorado River (Fig. 5). This geomorphic relation of the tuff and this valley implies that the valley existed prior to deposition of the tuff, which seems to conflict with the 19–20 Ma age of the tuff. Detailed map relations, however, suggest that this tuff was deposited in a paleovalley that was buried by basalt-rich debris flows, and later exhumed; these debris flows are now preserved as erosional remnants that cap ridges adjacent to the tuff-coated valley.

Relations of the 19–20 Ma ash-flow tuffs and siliceous intrusives to nearby Miocene basaltic flows are not clear. Larson et al. (1975) discussed evidence that basaltic flows of the White River uplift were erupted on a nearly level surface that sloped to the southwest away from the Park Range that forms a northern continuation of the Gore Range ~50 km north of the northeast edge of Figure 1. Miocene basaltic flows that later covered this erosional surface were widespread but not entirely continuous (Larson, et al., 1975; Kirkham and Scott, this volume), perhaps because the surface included topographic highs where flows were not deposited. Basaltic flows apparently were not

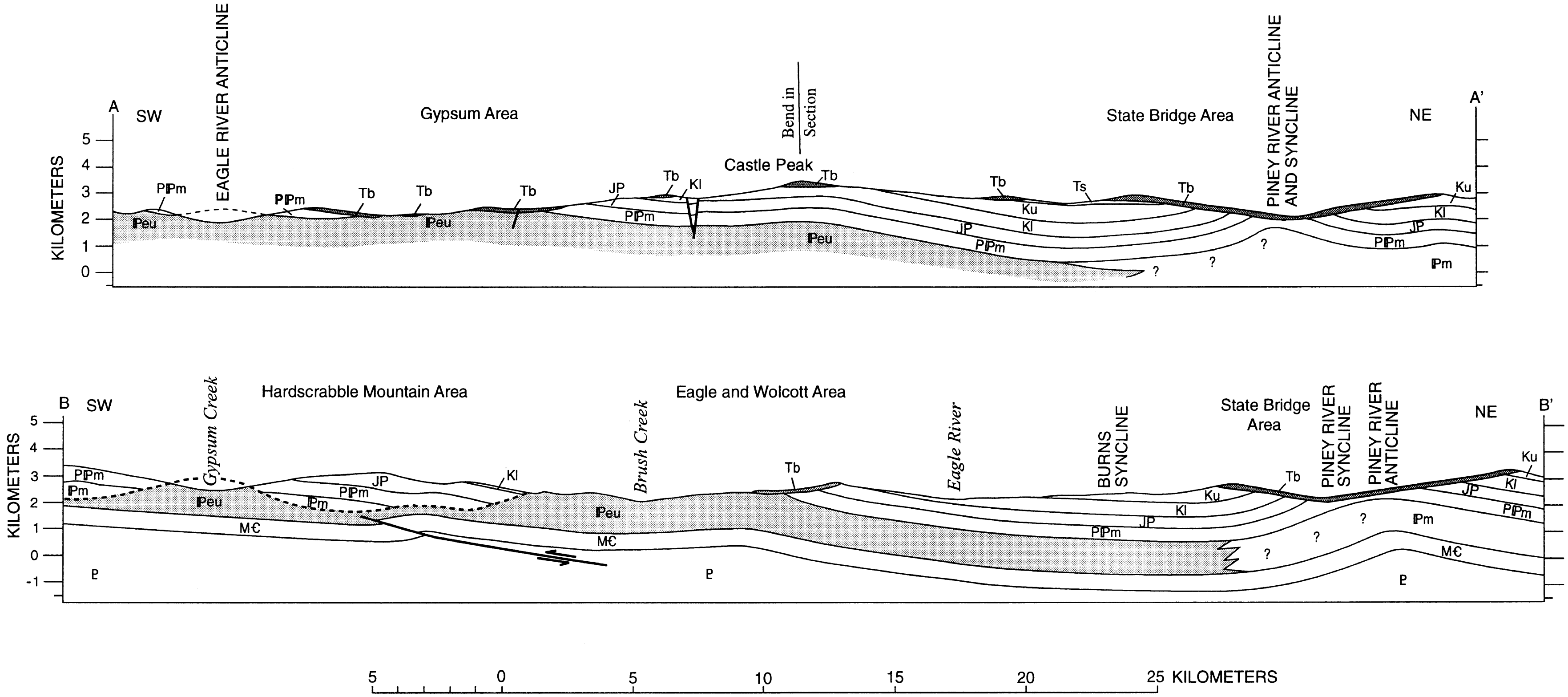

Figure 4. Generalized geologic cross sections A–A′ and B–B′ across the Eagle collapse center (based mostly on Tweto et al., 1978). Tb—late Tertiary basaltic flows (locally includes thin sandstone, gravel, and lacustrine strata); Ts—Tertiary sediments; Ku—Upper Cretaceous Pierre Shale; Kl—Cretaceous Niobrara and Benton Formations and Dakota Sandstone; JP—Jurassic Morrison and Entrada Formations, Triassic Chinle Formation, and Triassic to Permian State Bridge Formation; PIPm—Permian and Pennsylvanian Maroon Formation; IPm—Pennsylvanian Minturn Formation; IPeu—Pennsylvanian Eagle Valley Formation and Eagle Valley Evaporite; M€—Mississippian through Cambrian sedimentary rocks; P—Precambrian crystalline rocks. Thin line—contact; thick solid line—fault; thick dashed line—diapiric contact. Location of facies change from Eagle Valley Evaporite to Minturn Formation is queried in the vicinity of State Bridge. Locations of cross sections A–A′ and B–B′ are shown on Figure 3; cross sections show more detailed subdivision of rock units than is shown in Figure 3 sketch map.

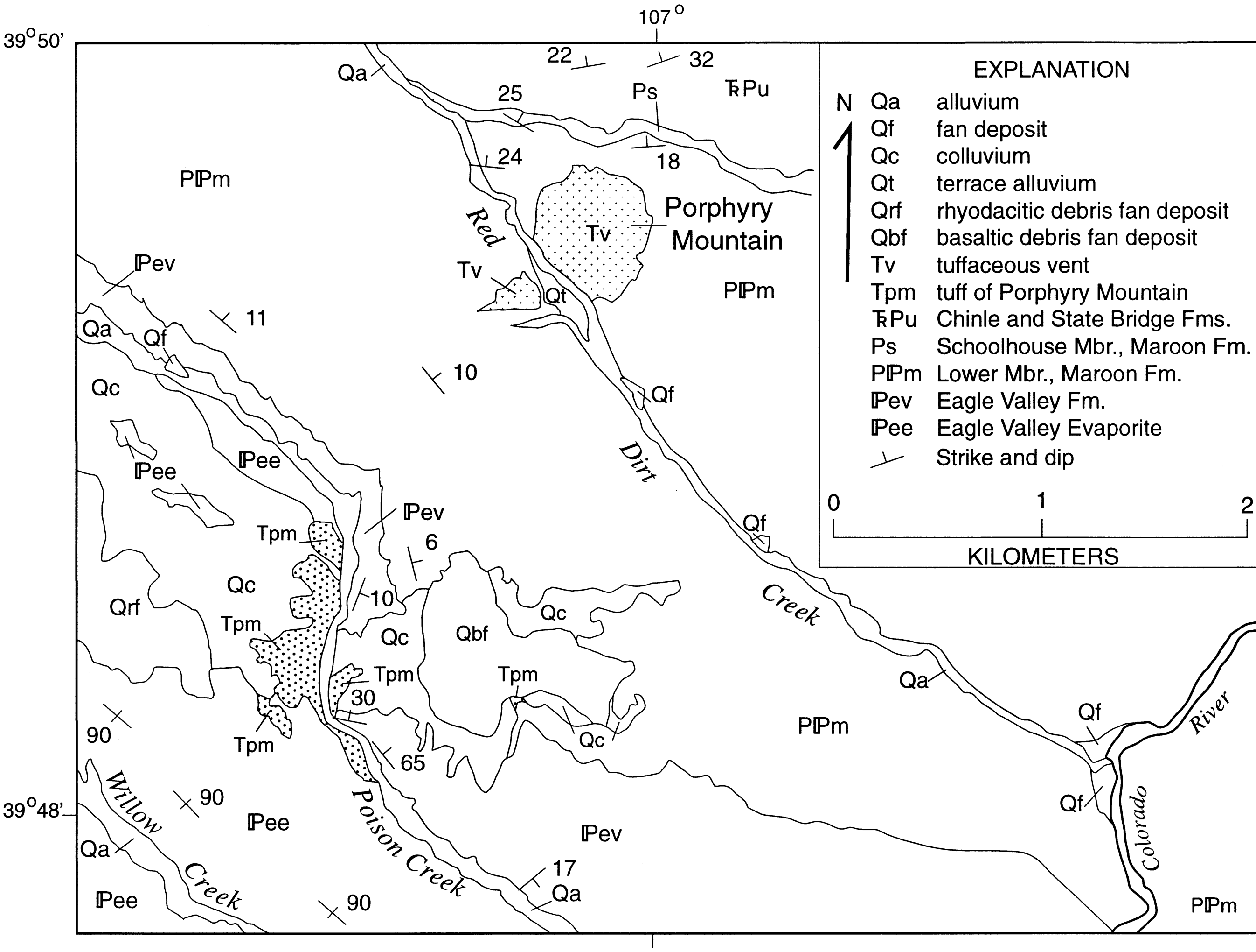

Figure 5. Map showing geologic features of the Porphyry Mountain area (modified from J.O. Stanley, 2001, University of Northern Colorado, unpub. mapping).

erupted on the early Miocene surface east and southeast of Porphyry Mountain at the time when 22–24 Ma flows were emplaced elsewhere in the region of the Eagle collapse center near Yarmony Mountain, State Bridge, Castle Peak, Gypsum, Eagle, and Wolcott. We speculate that during early Miocene time the Porphyry Mountain area may have been part of a topographic high that separated early Miocene basaltic flows of the White River uplift from those at Castle Peak and elsewhere in the Eagle and Colorado River basins. The sparse remnants of 19–20 Ma tuff, present at elevations of ~2.5 km in the Porphyry Mountain area, may represent remnants of this topographic high, where early Miocene ash deposits were deposited above adjacent and topographically lower parts of the surface that were being covered by basaltic flows. The ancestral Colorado River may have later followed the partly ash-covered, easily eroded strata in this elevated gap between the more resistant basaltic flows, resulting in topographic inversion in this area. The Eagle Valley Evaporite is exposed or present at shallow depth throughout the area of the inferred topographic high. During late Miocene and younger incision of the Colorado River, removal or flow of evaporite likely resulted in collapse of the 19–20 Ma surface that appears to be partly defined by the ash-flow tuff remnants at elevations of ~2.1–2.5 km; the lowest of these ash-flow tuff remnants is ~1 km lower in elevation than adjacent basaltic flows of the White River uplift and Castle Peak that occur at elevations of ~2.9–3.6 km.

Gypsum area

Geologic mapping and supporting paleomagnetic and geochemical data from early Miocene basaltic flows in the Gypsum quadrangle (Fig. 6) illustrate the character and history of evaporite dissolution and landscape modification in the western part of the Eagle basin. Clear evidence for late Cenozoic deformation of early Miocene basaltic flows is evident in the Gypsum area. Isotopic dating of and paleomagnetic data from these

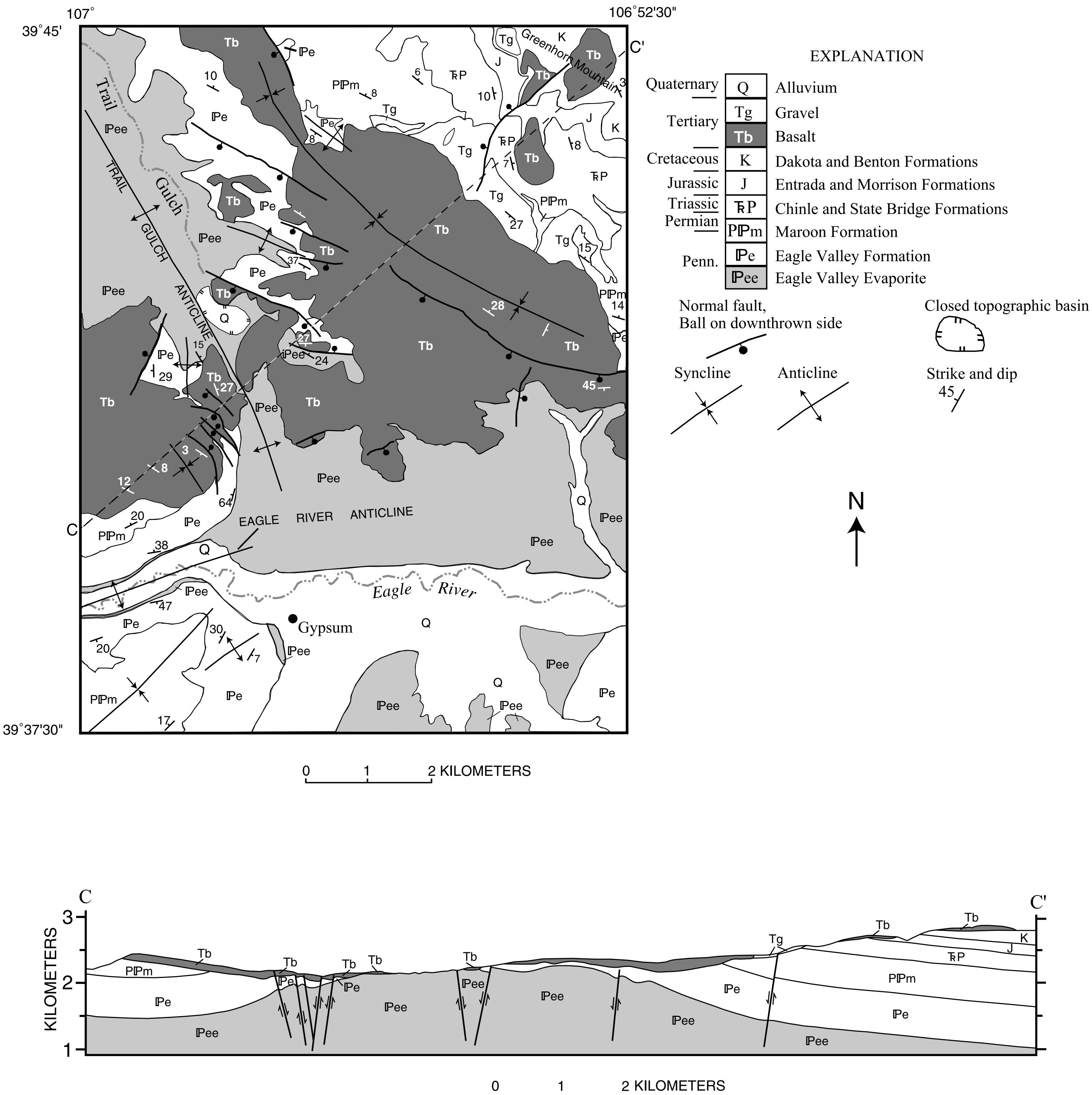

Figure 6. Generalized geologic map of the Gypsum 7½′ quadrangle and cross section C–C′ (after M.R. Hudson and D.M. Moore, 2001, U.S. Geological Survey, unpub. mapping). Most surficial units are omitted.

flows, as well as relations of flows to the Pennsylvanian evaporite and other underlying strata, indicate that late Cenozoic deformation of these flows was related to evaporite tectonism. However, geometric relations of the evaporite and younger strata to the flows also show some evidence for evaporite tectonism or regional tectonic deformation that predates early Miocene basaltic flows—the late Cenozoic deformation rotated and tilted pre-Miocene folds in strata that underlie the basaltic flows.

Thick masses of evaporite underlie two broad belts within the Gypsum quadrangle (Fig. 6). One belt of evaporite trends east-west across the quadrangle, underlies the Eagle River, and forms the core of the Eagle River anticline. The second belt of evaporite trends north-northwest across the northwestern part of the quadrangle, underlies Trail Gulch, and forms the core of the Trail Gulch anticline. Younger Paleozoic and Mesozoic formations generally dip away from these regions of thick evaporite to define the Eagle River and Trail Gulch anticlines, although in detail their structure is more complicated than that of simple anticlines. The Eagle River anticline is best expressed in the southwestern part of the map area (Fig. 6) by dips in the Eagle Valley and Maroon Formations. These dips progressively steepen toward the evaporite core. In contrast to the broad folds and faults in overlying formations, the structure of Eagle Valley Evaporite within the cores of both anticlines is typically complex. Small-scale folds with shapes ranging from chevron to polyharmonic are abundant within the evaporite and interbedded sandstone and limestone beds. Widmann (1997) studied many small folds within the Eagle River and Trail Gulch anticlines and documented that their axes generally parallel the east and north-northwest trends of the Eagle River and Trail Gulch anticlines, respectively. The trend and general confinement of these subsidiary folds to the evaporite core of the major anticlines suggests that the anticlines are diapiric in origin and that local flow of evaporite was directed perpendicular to the anticline axes, as well as upward within the cores of the anticlines.

Early Miocene basaltic flows constrain and provide a record of late Cenozoic deformation in the Gypsum quadrangle. Basaltic flows in the southwest part of the quadrangle and from the adjacent Dotsero quadrangle yielded isotopic dates of ca. 22–24 Ma (Larson et al., 1975; Streufert et al., 1997a; Kunk et al., this volume). Geochemical data, specifically ratios of Hf/Ta and La/Yb (Budahn et al., this volume), obtained from 25 basalt samples distributed across the Gypsum quadrangle, are distinct from those of middle and late Miocene basaltic flows that are common to the southwest in the Carbondale collapse center (Kirkham et al., this volume). These isotopic and geochemical data, and the lack of field evidence for major unconformities with the sequence of flows, verify that the basaltic flows can be used as a datum to evaluate deformation since the early Miocene. Basaltic flows in the Gypsum area range in elevation from ~2.9 km where they cap Greenhorn Mountain in the northeast to ~2.0 km north-northwest of Gypsum on the west flank of the Trail Gulch anticline; the difference in elevation results from a series of broad folds and discontinuous normal faults. Locally, the basalt flows dip steeply, and paleomagnetic data (Hudson et al., this volume) confirm that these dips reflect later tilt rather than primary dip. In cross section, flows flanking both sides of the Trail Gulch anticline lie in local, faulted topographic lows. A small closed topographic basin, or very large sinkhole, developed within the evaporite on the crest of the Trail Gulch anticline (Fig. 6). This basin is ~2 km long and 1 km wide, partly filled with surficial materials, and probably marks a local focus of young, late Cenozoic dissolution. A sequence of gravels, as thick as 50 m on the southwest flank of Greenhorn Mountain, may represent a paleoriver valley that incised through the early Miocene basalt. The outcrop pattern and the few measured dips within the gravel indicate that it was tilted southwest, like the early Miocene basaltic flows.

Deformation of the early Miocene basaltic flows in the Gypsum area is clearly linked to late Cenozoic evaporate flow and dissolution, but the subcrop pattern of Paleozoic and Mesozoic formations beneath the flows indicates that evaporite deformation was also active at earlier times. Cross section C–C′ (Fig. 6) illustrates that the basaltic flows overlap the Eagle Valley Evaporite and younger formations on both sides of the Trail Gulch anticline, indicating that the evaporite was already exposed in the core of the anticline before eruption of the basalt. Between the Miocene basalt and underlying Paleozoic and Mesozoic rocks, Tertiary sediment ranging from conglomerate to mudstone are locally exposed; these sediments are relatively thin and discontinuous and are not shown in Figure 6. The thickest section of these prebasalt Tertiary sediments (~40 m thick) underlies the area of maximum collapse of basaltic flows, southwest of the Trail Gulch anticline crest, suggesting that this was a local basin prior to early Miocene basalt eruption. On the southwest flank of Greenhorn Mountain, southwest-dipping basaltic flows and gravels overlie northeast-dipping Paleozoic and Mesozoic strata along an angular unconformity (Fig. 6). The geometry of these opposed dip relations suggest that late Cenozoic flow or dissolution of evaporite resulted in collapse of overlying strata, flows, and gravels. The collapse reduced the northeast dip of strata that previously dipped more steeply to the northeast, and this collapse-related back-tilting of strata is recorded by the southwest dip of the overlying flows and gravels. Similar tilting of older structures during late Cenozoic collapse was documented along the Grand Hogback monocline where it encounters the western margin of the Carbondale collapse center (Kirkham et al., 1996).

Wolcott area

The Wolcott area (Fig. 7) is mostly underlain by a gently to moderately, north- to northeast-dipping sequence of Pennsylvanian to Upper Cretaceous strata (Fig. 8). In the southwestern and south-central parts of the Wolcott area, the Eagle Valley Evaporite and overlying Eagle Valley Formation are tightly folded in a series of west-trending anticlines and synclines where these units are exposed at the base of the north-dipping sequence. The west-trending folds bend to the north in the southeastern part of the area, where they impinge on the broad western limb of the north-plunging Sawatch anticline that is present east and southeast of the east border of Figure 7. North of the Eagle River, in the northeastern part of the Wolcott area, the northerly plunging Ute Creek syncline deforms rock units as young as the Upper Cretaceous Benton Shale. This syncline appears to be a kink fold that formed along the western limb of the much larger Sawatch anticline during the Laramide orogeny (Lidke, 1998). Lidke (1998) interpreted the tight folds in the southern part of the Wolcott area as resulting from two

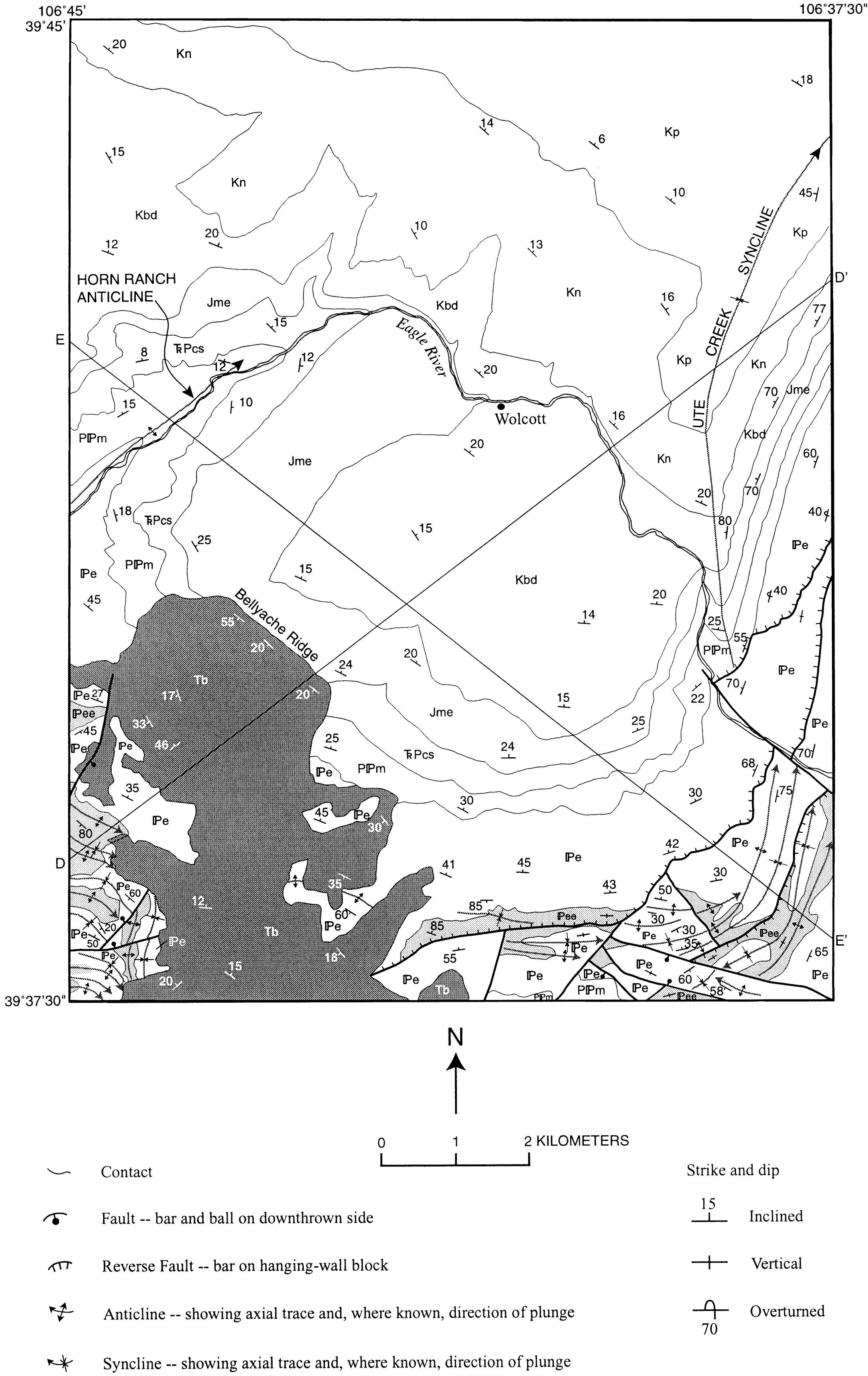

Figure 7. Generalized geologic map of the Wolcott 7½′ quadrangle (after Lidke, 1998). Surficial units are omitted. Tb—early Miocene basaltic flows (locally includes basal gravel); Kp—Upper Cretaceous Pierre Shale; Kn—Upper Cretaceous Niobrara Formation; Kbd—Cretaceous Benton Shale and Dakota Sandstone; Jme—Jurassic Morrison and Entrada Formations; TRPcs—Triassic Chinle Formation and Triassic to Permian State Bridge Formation; PIPm—Permian to Pennsylvanian Maroon Formation; IPe—Pennsylvanian Eagle Valley Formation; IPee—Pennsylvanian Eagle Valley Evaporite. Cross sections D–D′ and E–E′ are shown in Figure 8.

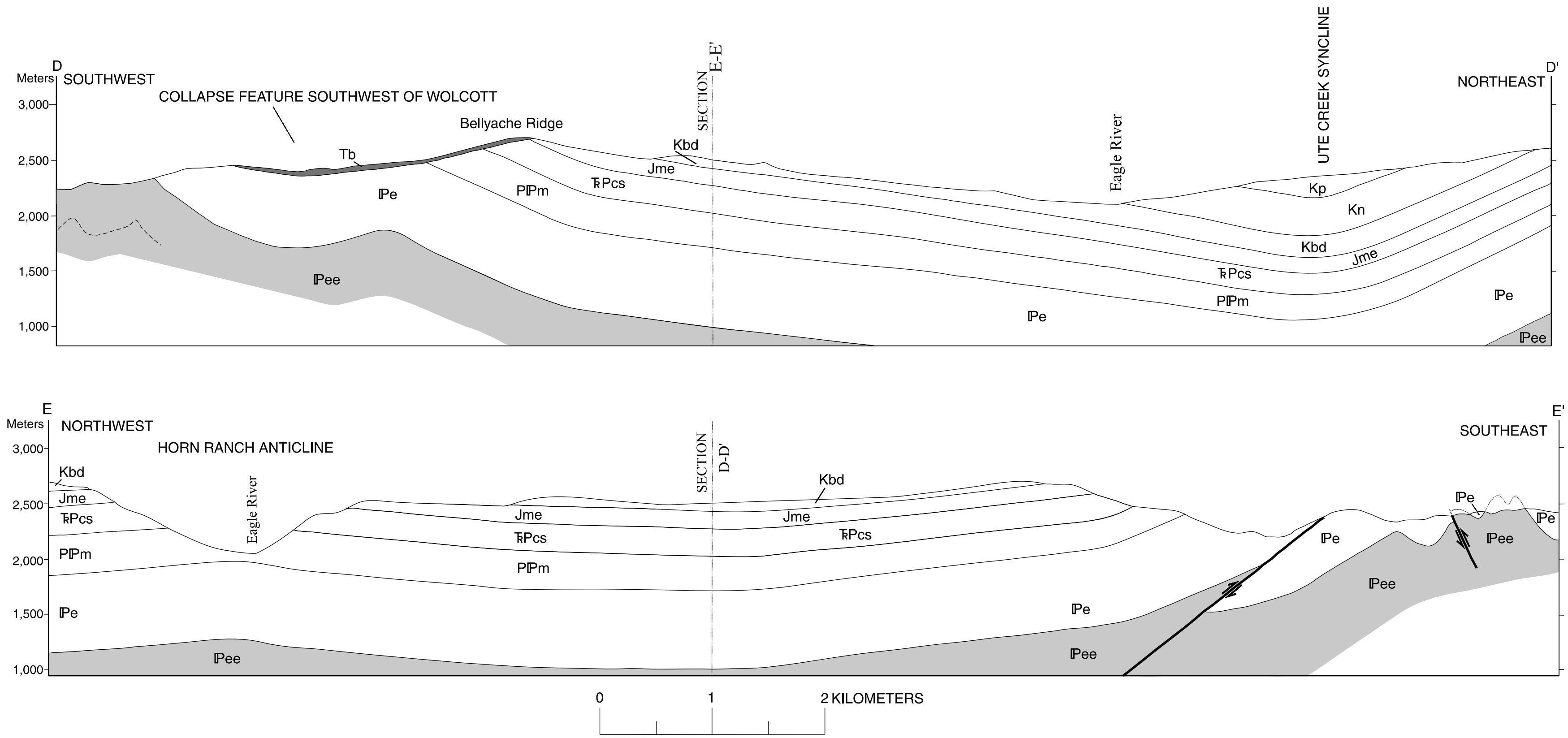

Figure 8. Generalized geologic cross sections D–D′ and E–E′ across parts of the Wolcott 7½′ quadrangle. See Figure 7 for locations of cross sections. Symbols are the same as those shown in Figure 7 except thin short-dashed line in subsurface of D–D′—bedding form line in ℙee.

phases of Laramide deformation, but the age of these folds is not tightly constrained. They are, however, older than early Miocene basaltic flows that unconformably overlie tightly folded evaporite and the Eagle Valley Formation in the southwestern part of the Wolcott area.

In the southwestern part of the Wolcott area, early Miocene basaltic flows unconformably overlie tightly folded evaporite and the Eagle Valley Formation. These flows have collapsed to form a northwest-trending, synclinal sag that is superimposed on previously deformed underlying rock units. The broad, northeast-trending, Horn Ranch anticline is present along the Eagle River northwest of the synclinal sag; this anticline may express upwelling of evaporite beneath an erosionally unloaded canyon carved out by the Eagle River.

Synclinal sag southwest of Wolcott. A prominent late Cenozoic collapse feature formed a northwest-trending, trough-like structure that is expressed in 22–23 Ma basaltic flows 5 km southwest of Wolcott (Fig. 7) (Lidke, 1998). The flows overlie a tightly folded to northeast-dipping sequence of rock units that range from the Pennsylvanian Eagle Valley Evaporite to Jurassic strata (Fig. 8, section D–D′). Along the southwest side of Bellyache Ridge that about marks the northeastern flank of the collapse feature (Figs. 7 and 8), these basaltic flows lie at an elevation of ~2750 m and dip ~20°–25° southwest toward a broad trough; within the trough the flows lie at an elevation of ~2320 m. These relations suggest at least 430 m of collapse of the basalt and underlying strata in the central part of the sag. Hubert (1954) recognized these collapsed basaltic flows and he suggested that the deformation was related to movement of the underlying evaporite. Larson et al. (1975) dated numerous basaltic flows in this region, but they did not date the flows southwest of Wolcott, nor mention that they were deformed. They did suggest, however, that the Wolcott flows probably correlated with their Group 1 (20–24 Ma) basaltic flows, which included flows they dated and noted were deformed in the Piney River syncline in the State Bridge area (Figs. 3 and 4). Recent geologic mapping in the Wolcott quadrangle (Lidke, 1998) and isotopic dates of ca. 22–23 Ma that were obtained from two samples of the basaltic flows in the Wolcott area (Kunk et al., 1997; Kunk and Snee; 1998; Kunk et al., this volume), confirm and refine Hubert's and Larson's conclusions and show that early Miocene (22–23 Ma) basaltic flows are deformed in a synclinal sag above evaporite.

The sag in the basaltic flows is superimposed on more tightly folded rocks of the Eagle Valley Formation and Eagle Valley Evaporite in the trough of the collapse feature. The geometric relations between the basalt and underlying strata suggest that late Cenozoic collapse was greatest in the axial region of the sag where the Eagle Valley Formation and Eagle Valley Evaporite directly underlie the flows (Fig. 8, D–D′). Some collapse or back-tilting of the northeast-dipping rock units beneath Bellyache Ridge, which marks the northeastern limb of the collapse feature, is also required, however, to produce the southwestward dip of the flows along this limb. This geometric relation of the orientation of layers in the underlying strata to those in the overlying flows, requires that the preexisting northeast tilt of the strata was reduced (back-tilted) during late Cenozoic deformation that tilted the overlying flows to the southwest. This is similar to back-tilting of strata beneath collapsed basaltic flows in the Gypsum area and along the western margin of the Carbondale collapse center (Kirkham et al., this volume).

Horn Ranch anticline. The Horn Ranch anticline is a broad northeast-plunging anticline that underlies the Eagle River valley in a steep-sided canyon ~5 km west of Wolcott (Fig. 7). Pennsylvanian to Cretaceous sedimentary rocks dip ~5°–15° northwest and southeast away from the axis of this anticline (Fig. 8, section E–E′). The Horn Ranch anticline involves Upper Cretaceous strata and may be a late Cenozoic structure related to downcutting of the Eagle River and resulting diapiric rise of the Eagle Valley Evaporite. The Eagle River anticline near Gypsum (Benson and Bass, 1955) also follows the Eagle River valley and is a late Cenozoic feature because it deforms early Miocene basaltic flows. We conclude that the Horn Ranch anticline is similar in origin to the Eagle River anticline and also related to late Cenozoic upwelling of the Eagle Valley Evaporite beneath the erosionally unloaded Eagle River valley.

Eagle area

Near the town of Eagle, the Eagle River is incised in Eagle Valley Evaporite, which is widely exposed along the river (Fig. 9). The Eagle River approximately coincides with the crudely defined boundary between two structural domains that are north and south of the Eagle River (Lidke, 2002). The domain north of the Eagle River is characterized by a locally broadly folded and faulted, but mostly homoclinal sequence of sedimentary rock units that dip moderately northward. The Eagle Valley Evaporite is exposed at the base of this sequence and strata as young as the Upper Cretaceous Niobrara Formation is exposed at the top of the sequence along the northern border of the Eagle quadrangle (Fig. 9). Several broad north-northwest–trending folds north of the river deform Upper Cretaceous rocks. The domain south of the Eagle River is underlain by the evaporite and overlying Eagle Valley Formation that display tight folds with diverse axial trends. These tight folds are at least in part a continuation of the tight folds in the southern part of the Wolcott quadrangle and, like those folds, they appear to predate unconformably overlying basaltic flows. Lidke (2002) concluded these folds probably date from earlier phases of deformation that probably include both local, evaporite-related deformation and regional tectonic deformation. Both north and south of the Eagle River, faults cut rocks as young as Miocene basaltic flows

Faulted erosional remnants of basaltic flows in the Eagle area (Fig. 9) strongly suggest that late Cenozoic collapse features near Gypsum are coeval and cogenetic with those southwest of Wolcott. Remnants of flows occur in three areas in the

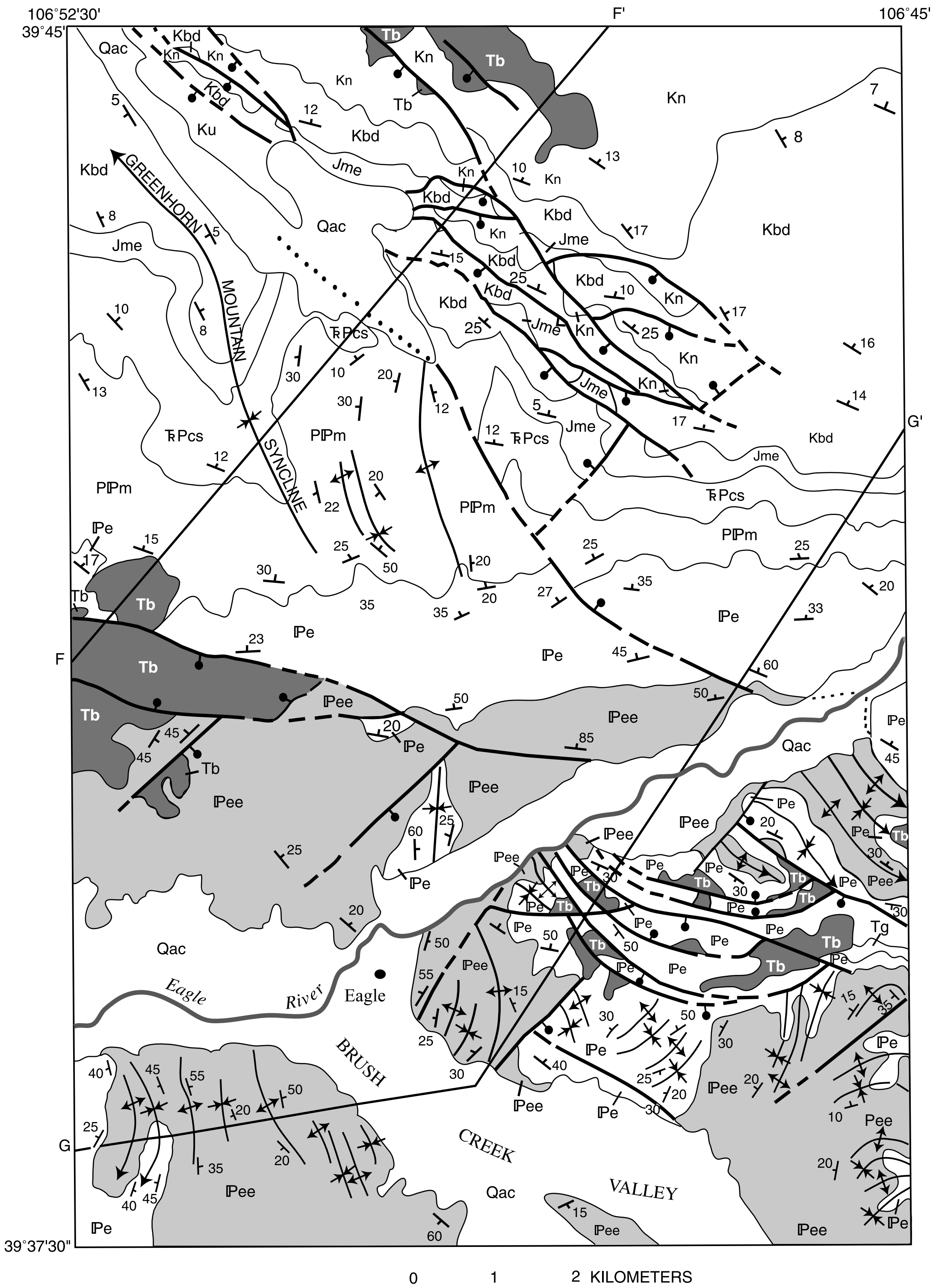

Figure 9. Generalized geologic map of the Eagle 7½′ quadrangle (after Lidke, 2002). Some surficial units are omitted. Symbols are the same as those shown in Figure 7 except Qac—Quaternary alluvial and colluvial deposits, Tg—Tertiary gravel, and Ku—Upper Cretaceous Niobrara Formation Benton Shale undivided.

Eagle quadrangle (Fig. 9). One area is located ~3 km east of Eagle, a second is centered ~5 km northwest of Eagle, and the third is ~10 km north of Eagle. The flows northwest and north of Eagle are newly mapped in the Eagle quadrangle (Lidke, 2002), and isotopic ages have not been obtained for any of the flows in the quadrangle. However, their ages can be inferred from the following relations: (1) the basaltic flows east of Eagle nearly connect to the east with the 22–23 Ma basaltic flows deformed in the sag southwest of Wolcott; (2) the flows northwest of Eagle connect to the west with flows north of Gypsum that have isotopic ages of ca. 22–24 Ma (Larson et al., 1975; Streufert, et al., 1997a; Kunk et al., this volume), and (3) flows north of Eagle nearly connect with flows at Castle Peak (Fig. 3) that have yielded isotopic ages of ca. 22–23 Ma (Kunk, et al., this volume). Therefore, it seems likely that the basaltic flows in the Eagle quadrangle are also early Miocene with ages in the range of 22–24 Ma.

Faulted basaltic flows east and northwest of Eagle. Basaltic flows east of Eagle unconformably overlie highly contorted rocks of the Eagle Valley Formation and Eagle Valley Evaporite (Fig. 10, section G–G′). These flows are cut by numerous linear to arcuate, northwest- to north-trending faults that locally form horsts and grabens; some of these faults are not traceable into or die out in the evaporite. The overall geometry of rock units shown in Figure 10 (Section G–G′) suggests that these basaltic flows overlie a syncline flanked by two broad, internally folded, anticlines that about coincide with the Eagle River and Brush Creek valleys.

Basaltic flows northwest of Eagle unconformably overlie the Eagle Valley Evaporite and Eagle Valley Formation and are cut by west-northwest–trending faults, which form the northwest-trending graben partly shown along the southwestern end of section F–F′ (Fig. 10). Directly northeast of this graben, mapped relations indicate that basaltic flows dip ~10°–15° southwest; underlying Pennsylvanian to Permian rocks dip 15°–25° northeast. Thus, the relation of the flows to the underlying rock units is similar to relations mapped in the Gypsum and Wolcott areas and similarly requires late Cenozoic back-tilting of underlying rock units during deformation that produced the southwest dip in the overlying basaltic flows. Removal of evaporite at depth during the late Cenozoic is a mechanism that most readily accounts for the tilting of the basaltic flows and back-tilting of underlying strata.

Faulted basaltic flow remnants east and northwest of Eagle probably are continuations of collapsed, relatively low-lying basaltic flows present southwest of Wolcott and north of Gypsum. The flow remnants east and northwest of Eagle occur at elevations from ~2180 to 2360 m, about the same as the lowest flows both north of Gypsum (2040 m) and southwest of Wolcott (2320 m). The probable connection of collapsed flows in the Gypsum and Wolcott areas with flows east and northwest of Eagle (Fig. 3), suggests that a northwest-trending sag extends from southwest of Wolcott through Eagle and into the region north of Gypsum.

Basaltic flows and northwest-trending graben north of Eagle. Basaltic flows along the north edge of the quadrangle, ~10 km north of Eagle (Fig. 9), are flat-lying and overlie Upper Cretaceous shales that dip ~10°–15° northeast. These faulted flows are preserved at elevations as high as ~3350 m; they are ~1000 m higher than the basaltic flows east and northwest of Eagle, but only ~100 m lower than the highest, nearby 22–23 Ma basaltic flows (Kunk et al., this volume) that cap Castle Peak ~2 km to the northwest (Fig. 3). The basaltic flows along the northern border of the Eagle quadrangle are cut by northwest-striking, down-to-the-southwest, normal faults. These southwest-dipping normal faults connect in anastomosing patterns and appear to be linked with a northwest-striking, northeast-dipping, normal fault to form a graben southwest of the flows (Fig. 9, section F–F′). This graben may be a brittle expression of collapse related to evaporite removal at depth beneath the Eagle Valley Formation (Fig. 10, section F–F′). These high flows in the Eagle quadrangle probably once connected with nearby 22–23 Ma basaltic flows at Castle Peak and probably also are correlative with the 22–24 Ma, collapsed basaltic flows at low elevations near Eagle and Gypsum. Evaporite removal beneath the graben and adjacent areas during the late Cenozoic may have produced the graben, and may also account for the lower elevation and southwesterly dip of collapsed basaltic flows near the southwestern end of section F–F′.

Existence of river-valley anticlines near Eagle. The presence of an anticline along the Eagle River near Eagle would provide a connection between the Eagle River anticline near Gypsum and the Horn Ranch anticline between Eagle and Wolcott. The existence of an anticline along the Eagle River valley in the Eagle quadrangle, however, is not obvious, although there is some suggestion of arching of strata across the valley. For example, in Figure 10 (section G–G′), the Eagle Valley Formation and Eagle Valley Evaporite appear to be broadly arched across both the Eagle River and Brush Creek valleys. An anticlinal feature along this part of the river would at least in part be superimposed on preexisting, erratically trending folds in the evaporite and Eagle Valley Formation, and these preexisting folds may obscure the expression of an anticlinal feature along the Eagle River. Some of the north-trending folds adjacent to and south of the Eagle River plunge southward (Fig. 9), and that plunge may reflect warping of these folds in the south limb of a younger anticlinal feature along the Eagle River.

Hardscrabble Mountain area

Tweto et al. (1978) interpreted Hardscrabble Mountain southwest of Eagle (Figs. 3 and 4), as a 30 × 10 km block of gently north-dipping Triassic to Cretaceous strata downdropped into Eagle Valley Evaporite. Tweto (1977) proposed that the evaporite flowed diapirically beneath and around the mountain. Seismic reflection data (Perry et al., this volume; their Figure 8) confirm this conclusion and add significantly to it. The seismic data show that the faults, which drop the mountain into the

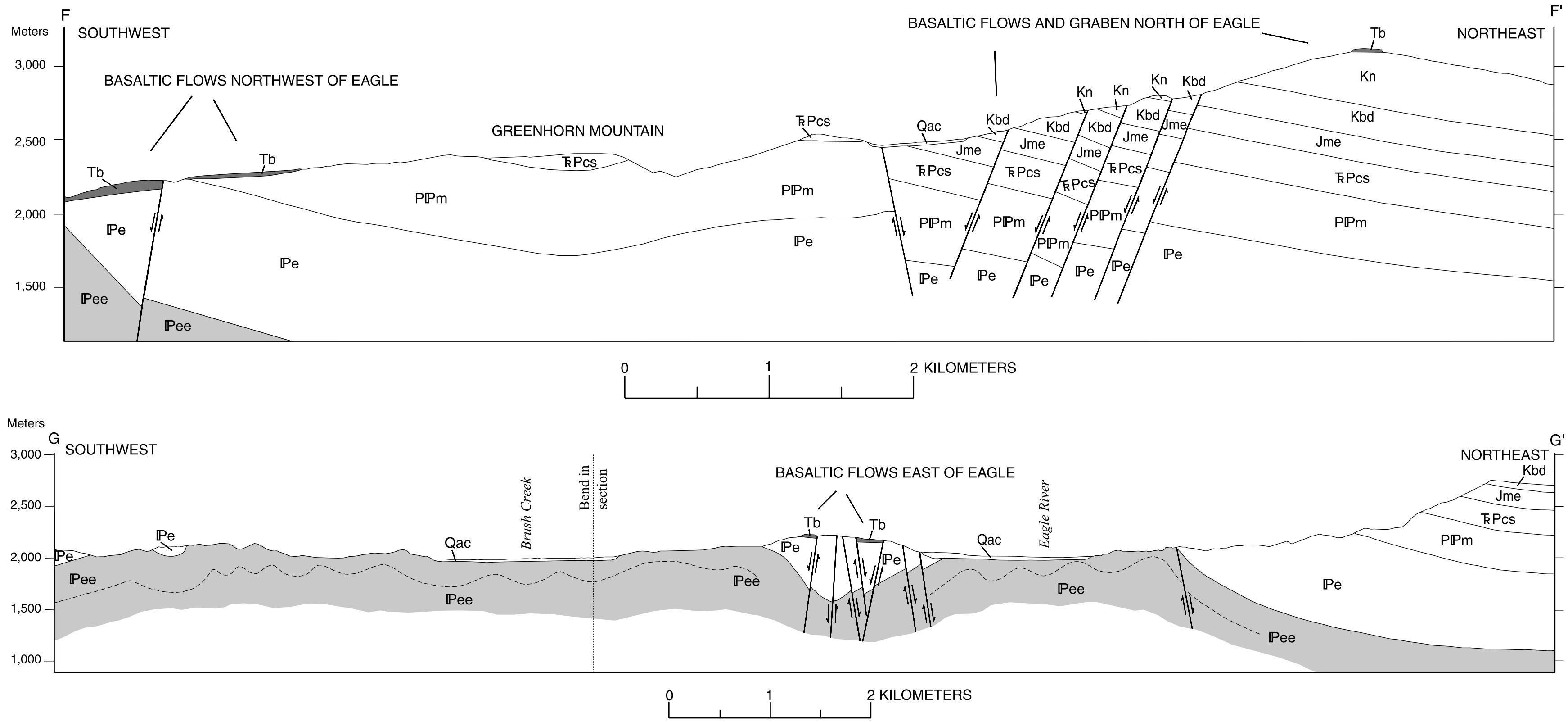

Figure 10. Generalized geologic cross sections F–F′ and G–G′ across parts of the Eagle 7½′ quadrangle. See Figure 9 for location of cross sections. Symbols are the same as those shown in Figure 7 except thin, short-dashed line in subsurface of G–G′—bedding form line in ℙee, and Qac—Quaternary alluvial and colluvial deposits.

Pennsylvanian evaporite, do not offset older Paleozoic strata beneath the evaporite; only a small, unrelated Laramide or late Paleozoic thrust fault offsets the older strata below the center of the mountain. The seismic data also show that the evaporite is thin to absent beneath the Hardscrabble Mountain block, but quite thick to the north and south, strongly suggesting flow of evaporite from beneath the block and into adjacent areas. Evaporite deformation probably took place at least twice, once during deposition of the unusually thick State Bridge Formation during the Permian and Triassic and again during late Cenozoic time. The unusual thickness of the State Bridge suggests that the block was subsiding within the evaporite during State Bridge deposition. The excess thickness of the State Bridge Formation is ~1.5 km, which is about equivalent to the thickness of evaporite north and south of the block. The tilt of the Mesozoic homoclinal block to the north requires post–State Bridge deformation, probably during the late Cenozoic.

Avon area

The Eagle Valley Evaporite is exposed along both sides of the Eagle River valley near Avon (Fig. 3). A west-trending, evaporite-cored arch coincides with the Eagle River valley in this area. The arch apparently deforms the broad, north-plunging nose of the Laramide age Sawatch anticline and subsidiary, north-trending folds related to it. East of Avon, the evaporite intertongues with siliciclastic strata of the Minturn Formation and the evaporite pinches out abruptly ~7 km west of Vail (Tweto et al., 1978; Scott et al., 2002).

The evaporite and overlying Eagle Valley Formation are deformed in broad to tight, mostly north-trending folds near Avon and Edwards (Lidke, 1998; D.J. Lidke, unpub. geologic mapping). These folds appear to be subsidiary to the much larger Sawatch anticline that formed during the Laramide orogeny. Many of these folds plunge away from the Eagle Valley, suggesting that they are arched across the valley to form an east-west-trending anticlinal feature cored by evaporite. These relations are similar to those along the Eagle River near Gypsum and Eagle, and suggest upwelling of evaporite along the Eagle River valley near Avon. Scott et al. (2002) noted very irregular attitudes in the Eagle Valley and Maroon Formations near evaporite ~3.5 km east of Avon, and concluded that deformation of these formations reflected movement of the underlying evaporite. Basaltic flows are absent in the Avon area, so a late Cenozoic age for evaporite tectonism in this area is not determined. It seems likely, however, that the evaporite-cored valley of the Eagle River near Avon and Edwards is related to late Cenozoic valley incision that would have erosionally unloaded the valley area, probably triggering upwelling of evaporite at depth along the valley.

The intertonguing and pinch-out of the evaporite east of Avon, between Avon and Vail, is shown on the Leadville 1° × 2° quadrangle (Tweto et al., 1978) and briefly discussed in Scott et al. (2002). The evaporite is poorly exposed where it pinches out to the east into the Minturn Formation. It is not known if the abrupt pinch-out of evaporite is entirely depositional in character, is in part structural, or related to movement of evaporite at some time after it was deposited. North of Avon, the evaporite and Minturn Formation are not exposed, and the distribution and geometry of the evaporite in the subsurface is not known. The evaporite probably pinches out within the Minturn Formation somewhere north or northeast of Avon.

State Bridge area

About 18 km north-northwest of Avon, early Miocene basaltic flows are deformed in the Piney River syncline near State Bridge (Fig. 3). Wanek (1953) first noted the syncline, which is portrayed in Figure 4. Tweto et al. (1978) used Wanek's mapping, along with mapping by Donner (1949), Schmidt (1961), Brennan (1969), and their own reconnaissance mapping, to compile the State Bridge area of the Leadville 1° × 2° quadrangle. The area containing the syncline has not been mapped more recently and never mapped in much detail. Most of the area south of the Colorado River is private and inaccessible. Isotopic dates from flows in the State Bridge area are consistently in the 22–24 Ma range (York et al., 1971; Larson et al., 1975; Kunk et al., this volume), which is similar in age to basalts at Castle Peak and in the sag in the Gypsum–Wolcott area. Although the State Bridge syncline is an obvious large feature on the Leadville 1° × 2° quadrangle (Tweto et al., 1978), until recently little has been speculated about its late Cenozoic age and origin. Erslev (2001) interpreted the syncline as a late Cenozoic compressional feature based on ongoing studies of thrust faults and slickenlines in the Cretaceous Dakota Sandstone that locally and unconformably underlies the flows. We speculate that the syncline may be an evaporite-related sag based on similarity to the sag in the Gypsum–Wolcott area, and based on limited recent reconnaissance field studies near State Bridge, mostly north of the Colorado River. Information that may argue against a sag origin for the syncline includes (1) the data of Erslev (2001), (2) the apparent absence of exposures of evaporite in the vicinity of State Bridge, and (3) the possible absence of evaporite in the subsurface due to facies changes related to intertonguing with Minturn Formation.

Erslev (2001) favored a compressional origin for this syncline based on identification of two sets of thrust faults and related slickenlines in the Cretaceous Dakota Sandstone that is present beneath and near the deformed flows in the State Bridge area. The younger of the two sets shows north-northeast–trending slickenlines along faults; these were interpreted as being coeval with formation of the syncline, and it was suggested that both may be related to mid-Tertiary transfer of right-lateral strike-slip faulting in New Mexico to transpressional thrust and strike-slip faulting in north-central Colorado. To our knowledge the thrust and strike-slip faults and associated slickenlines are not developed in the early Miocene flows in the State Bridge area. Those identified in the Dakota Sandstone could represent the two or more episodes of Laramide compression that Erslev (2001) and numerous other authors have identified in nearby areas and elsewhere in the Front Range. The structures in the Dakota Sandstone can only be shown to be Cretaceous or younger in age and cannot definitively be linked with formation of the late Cenozoic synclinal feature in the State Bridge area.

The apparent absence of evaporite and presence of Minturn Formation in the vicinity of the State Bridge, adds uncertainty to the existence of evaporite in the subsurface near State Bridge, and consequently, may argue against an evaporite-related origin for the syncline. At the south end of the syncline, the Minturn Formation is poorly exposed in the core of a Laramide anticline on which the syncline is superimposed (see Figures 3 and 4). Northwest of the syncline, near the town of McCoy, sedimentological and paleontological studies of the Minturn Formation and its limestones led Houck (1991, 1993, and 1997) to conclude that the limestones were not deposited in a highly saline environment, where evaporite would be expected. However, a few kilometers east of Avon, where the evaporite pinches out abruptly, nearby fossiliferous limestones in the Minturn also do not appear to record highly saline conditions. Indicators of highly saline environments perhaps should not be expected, even in limestones that have a close stratigraphic proximity to evaporite, because the limestones may mark times of elevated sea level and less saline conditions related to accumulation and ablation of Gondwanan ice centers, as discussed by Schenk (1989). The exposures of Minturn Formation at the south end of the syncline and those studied northwest of the syncline near McCoy, provide the only exposures of Middle Pennsylvanian rocks of either the Minturn Formation or Eagle Valley Evaporite in the area north of the Avon. One or both of these Middle Pennsylvanian units must be present in the subsurface in the area between Avon and State Bridge, but the distribution of these units in the subsurface north of Avon is not known. Consequently, information that can be inferred from the character of the pinch-out of evaporite in the Minturn Formation east of Avon, combined with the unknown relations of the Minturn Formation and evaporite in the subsurface between the Avon and State Bridge areas, allow the interpretation that dissolution and flow has largely removed a local depositional center of evaporite that once existed beneath the State Bridge area.

Other reasons to suspect that evaporite-related collapse may have created the syncline in the State Bridge area are speculative, but include recent, reconnaissance field studies, a saline spring near McCoy, limited seismic reflection information, and the similarity of the syncline to the sag present in Gypsum–Wolcott area. Recent reconnaissance field studies in the State Bridge area by T.L.T. Grose (Colorado School of Mines) and R.B. Scott (U.S. Geological Survey) found no evidence for a compressional origin of the syncline, but did identify some evidence suggestive of extension and normal faulting of basaltic flows, which are more indicative of collapse. On the north side of the Colorado River, evidence for high-angle faults exists in strata older than the flows but the sense of movement for these faults was not determined. South of the river in the basaltic flows and interbedded Browns Park Formation, T.L.T. Grose (Colorado School of Mines) found evidence of pull-apart structures, chaotic structures, normal faults, and slump features. In inaccessible areas south of the river, aerial photography provided some indirect evidence for continuation of the extensional features seen in accessible areas. Dissolved constituents in a warm saline spring near the town of McCoy include 485 mg/L of sodium, 321 mg/L of chloride, 95 mg/L of calcium, and 475 mg/L of sulfate (R.B. Scott, 2001, written commun.). Although these concentrations are not greatly elevated, they are significantly higher than fresh water and may suggest evaporite dissolution at depth. About 25 km northwest of McCoy, a northeast-trending seismic reflection line displays at least four normal faults that show as much as 15 m of offset in the Maroon and Minturn Formations. These faults, however, consistently terminate at depth before reaching the underlying Leadville Limestone. These relations are similar to faults that terminate at depth in evaporite beneath Hardscrabble Mountain; and these relations may indicate the presence of evaporite at depth, near the base of the Minturn Formation, in the area northwest of McCoy. A final observation involves the apparent absence of expression of the syncline in strata that underlie the basaltic flows, which mostly reflect an older anticline; these relations are similar to relations of underlying strata to basaltic flows in the sag of the Gypsum–Wolcott area. These local and regional relations of the late Cenozoic syncline near State Bridge, suggest to us that it is a sag related to removal of evaporite at depth.

POST–0.64 MA EVAPORITE-RELATED DEFORMATION NEAR EAGLE BASED ON CORRELATION AND FIELD RELATIONS OF VOLCANIC ASH DEPOSITS

Known and probable Lava Creek B ash deposits cap terrace remnants of Pleistocene gravel near Dotsero and east of Eagle (Fig. 2) Near Dotsero at the east end of Glenwood Canyon, volcanic ash overlies fluvial gravel in terrace remnants ~90 m and ~65 m above the Colorado River (Streufert et al., 1997a) (Figs. 1 and 2). The higher ash was identified by Izett and Wilcox (1982) as the Lava Creek B ash; it was redated at 0.64 Ma by Lanphere et al. (2002). Lava Creek B is the youngest of three (0.64, 1.27, 2.02 Ma) far-traveled ashes from the Yellowstone caldera complex (Izett and Wilcox, 1982). Streufert et al. (1997a) reported that G.A. Izett (1996, personal commun.) identified the ash on the lower terrace remnant as one of the Yellowstone-derived ashes, but they noted that additional work is needed to determine if it is also Lava Creek B. The lower ash along the Colorado River near Dotsero probably is also Lava Creek B, because there are no known younger ashes at lower levels in the region; however, the lower ash is poorly exposed beneath colluvium and it may be a reworked colluvial deposit that was derived from the higher ash. About 26 km to the east (~6 km northeast of Eagle), Lidke (2002) recognized ash on or within mainstream terrace deposits ~65 m above the Eagle River. The ash along the Eagle River was chemically correlated by Andrei Sarna-Wojcicki (1998, written commun.) with the Lava Creek B from the Yellowstone caldera complex and with the higher ash at the east end of Glenwood Canyon.

The differences in the heights of the 90-m ash near Dotsero and the 65-m ash near Eagle could be due in part to differences in the thickness of valley-floor sediments near these ashes; however, depths to bedrock beneath the valley floors near these ashes are similar. Along the Colorado River, near its junction with the Eagle River ~4 km upstream from the ash locality at the east end of Glenwood Canyon, depth to bedrock is ~20 m. Depth to bedrock ~3 km downstream from the Glenwood Canyon ash locality is locally >30 m (Colorado Department of Transportation, 2001, unpub. data). Farther downstream in the eastern half of Glenwood Canyon, depth to bedrock is locally >60 m (J.L. White and R.M. Kirkham, 1997, Colorado Geological Survey, unpub. Friends of the Pleistocene guidebook). At the town of Eagle, ~6 km downstream of the ash locality along the Eagle River, the depth to bedrock is ~20 m. About 6 km upstream of this ash locality it is locally >26 m (Colorado Department of Transportation, 2001, unpub. data). This depth to bedrock information combined with the height of the higher Dotsero ash above stream level (90 m), suggest an average incision rate of 0.17 m/k.y. during the past 0.64 m.y. for the Colorado River near the east end of Glenwood Canyon. This rate is compatible with an average rate of incision of greater than or equal to 0.15 m/k.y. for the Colorado River during the past 0.64 m.y. (Dethier, 2001) and 0.24 m/k.y. for the Colorado River in Glenwood Canyon during the past 3 m.y. (Kirkham et al., this volume). The incision rate implied by the 65-m height of the ash near Eagle is ~0.13 m/k.y., which is lower than the rates reported by Dethier (2001) and Kirkham (this volume).

Field relations suggest that it is unlikely that the ash deposits near Dotsero were displaced after deposition, whereas, the ash deposit near Eagle probably has collapsed. The two ash deposits at the east end of Glenwood Canyon (near Dotsero) are underlain by the Belden Formation, which only locally contains thin beds of evaporite, and no faults are shown between these ash deposits (Streufert et al., 1997a). It is unlikely that the dissolution of thin and erratic evaporite beds in the Belden Formation could account for the 25 m difference in elevation of the lower and higher ash deposits near Dotsero. It seems likely that the lower ash was derived from the higher ash, probably by slope processes. The ash deposit near Eagle, however, overlies gravel that rests on the Eagle Valley Evaporite. The difference in height between the ash deposits that have been identified as the 0.64 Ma Lava Creek B, the 90-m ash at the east end of Glenwood Canyon and the 65-m ash near Eagle, suggests at least 25 m of collapse of gravel and ash deposits that overlie evaporite near Eagle during the past 0.64 m.y.

CONCLUSIONS

Previous studies documented late Cenozoic evaporite-related deformation in the region of the Eagle collapse center as evidenced by the Eagle River anticline near Gypsum and the sag of basaltic flows south of Wolcott. Recent geologic mapping, isotopic dating, sparse geochemical analyses, and paleomagnetic studies of Miocene basaltic flows, as well as evaluation of seismic data, show evidence for more widespread late Cenozoic evaporite-related tectonism. Deformed early Miocene (22–24 Ma) basaltic flows provide a time constraint and obvious evidence for late Cenozoic deformation in the region.

At Castle Peak, the highest point in the Eagle collapse area, 22–23 Ma basaltic flows lie at altitudes of ~3.0–3.5 km, similar to altitudes of more extensive flows that cap the White River uplift, west of this collapse region. The high-standing Castle Peak basaltic cap apparently has not collapsed, or collapsed little, suggesting that evaporite-related collapse was not ubiquitous, nor equally distributed, throughout the Eagle collapse area. High-level basaltic flows at Castle Peak represent a small erosional remnant of a previously more extensive basaltic plateau that provides a high-level datum described by Kirkham and Scott (this volume). Geologic relations discussed for the Porphyry Mountain area suggest that a topographic high may have separated the flows that cap the White River uplift from flows of similar elevation at Castle Peak. Because strata that formed this high area were much more easily eroded than adjacent flow-capped areas, incision of the ancestral Colorado River probably caused topographic inversion in this region and this inversion probably was accentuated by collapse related to dissolution or flow of underlying evaporite.

Elsewhere in the Eagle collapse center, to the south, southwest, southeast, and northeast of Castle Peak, deformed early Miocene (22–24 Ma) basaltic flows are present at elevations ~1 km lower than the flows at Castle Peak. The relatively low-lying, basaltic flows near Gypsum, Eagle, and Wolcott are cut by discontinuous, linear to arcuate normal faults and show evidence of having sagged downward to form synclinal sags above underlying Pennsylvanian evaporite. Based on these deformed basaltic flows, we conclude that a northwest-trending, synclinal sag extends from south of Wolcott, ~25 km through the Eagle area and into the area north of Gypsum.

Early Miocene basaltic flows near State Bridge are similarly deformed in a northwest-trending synclinal sag. Although this deformation in the State Bridge area is obviously late Cenozoic in age, evidence to indicate that it is evaporite-related is inconclusive. Based on available data and the similarity of this sag feature to the sag in the Wolcott–Gypsum area, we suggest that late Cenozoic flow and dissolution may have removed a local depositional center of evaporite beneath the State Bridge area.

Evaporite-cored anticlines are present in several localities along the Eagle River valley and some or all of these anticlines are late Cenozoic in age and probably related to late Cenozoic incision of the Eagle River and rise of the of evaporite beneath the river valley. Benson and Bass (1955) documented the Eagle River anticline near Gypsum. The anticline deforms early Miocene basaltic flows and they concluded it reflects diapiric rise of evaporite beneath the erosionally unloaded valley of the Eagle River. Between Eagle and Wolcott, the Horn Ranch anticline may also reflect evaporite diapirism beneath the Eagle Valley. Near Eagle and farther east near Avon, westerly trending, evaporite-cored anticlinal features along the Eagle River valley appear to deform older northerly trending folds. Like the Eagle River anticline, these other anticlinal features appear to be related to upwelling of evaporite that probably occurred during late Cenozoic incision of the Eagle River.

Sparse remnants of Lava Creek B ash (0.64 Ma) overlie Pleistocene terrace gravels near Dotsero and east of Eagle; the difference in elevation of ash deposits at these localities implies post-0.64 Ma deformation. The Lava Creek B near Eagle is in the central part of the collapse center and this ash appears to be displaced by post-0.64 Ma collapse. Although correlation of fluvial deposits overlain by the Lava Creek B is not well established, the correlation presented implies at least 25 m of post-0.64 Ma collapse near Eagle that probably is related to dissolution or flow of underlying evaporite.

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