Neogene basins of the northern Rio Grande rift: partitioning and asymmetry inherited from Laramide and older uplifts

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Abstract

Three asymmetric Neogene basins in the northern Rio Grande rift of New Mexico and Colorado — the San Luis basin, the upper Arkansas River graben, and the Blue River graben — are tilted toward large flanking normal faults and lie astride the similarly asymmetric Late Cretaceous–early Tertiary (Laramide) San Juan–San Luis, Sawatch, and Front Range–Gore Range uplifts, respectively. The steep, thrust-faulted side of each uplift is on the same side as the down-rotated side of each of the Neogene basins. In addition, the direction of stratal tilt changes northward across the Villa Grove accommodation zone from east in the San Luis basin to west in the upper Arkansas River graben. This accommodation zone coincides approximately with the northward change from the east-directed San Juan–San Luis uplift to the west-directed Sawatch uplift. These observations, supported by seismic-reflection studies across the San Luis basin and studies of several other superimposed pairs of rift basins and Laramide uplifts, suggest that the basin-bounding normal faults are listric and merge at depth with the older thrusts, which are also listric and root into the crust at about 15–16 km. The Blue River graben is complicated by lack of basin fill and a thrust history along the west side of the Gore Range that is at least as old as late Paleozoic. Nonetheless, the Neogene valley is demonstrably tilted west and lies astride an overall west-directed thrust system, similar to other thrust-and-basin relationships in the northern Rio Grande rift. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Rio Grande rift; Colorado; Laramide orogeny; Neogene extension; inherited structure

1. Introduction

The Rio Grande rift extends northward from New Mexico into the heart of the southern Rocky Mountains, where the deep basin fill that defines major rifting terminates at the north end of the upper Arkansas River Valley near Leadville, Colorado (Tweto, 1979; Fig. 1). However, Neogene normal faults and grabens that are approximately coeval with formation of the Rio Grande rift can be traced along trend at least as far north as the Wyoming border; the Blue River graben is the largest of these northemmost rift structures. In Colorado and northern New Mexico, the Rio Grande rift developed along the axial zone of the Late Cretaceous–early Tertiary (Laramide) San Juan–San Luis uplift (Tweto, 1975, 1979; Chapin and Seager, 1975; Cordell, 1978; Eaton, 1979; Chapin and Cather, 1994; Russell and Snelson, 1994), which, in turn, developed along
Fig. 1. Map showing major tectonic features of the Colorado portion of the Rio Grande rift, simplified and modified from Tweto (1979). Cross-sections A–A', B–B', and C–C are shown in Fig. 3. AG = upper Arkansas River graben; APF = Antelope Pass normal fault; BRF = Blue River normal fault; BRG = Blue River graben; CF = Castle Creek fault zone; ET = Elk Range thrust zone; GF = Gore fault; GHM = Grand Hogback monocline; K = Kremmling; KT = Kerber Creek thrust; L = Leadville; MR = Mosquito Range; PP = Poncha Pass; S = Salida; VGAZ = Villa Grove accommodation zone; WMP = western Middle Park basin; WRT = Williams Range thrust.
structures that were as old as Proterozoic (Tweto, 1979).

Stratal tilt within basins of the Rio Grande rift alternates from east to west, segmenting the rift system (Chapin and Cather, 1994; Russell and Snelson, 1994) similar to the East African rift (e.g., Bosworth et al., 1986). Each segment of the Rio Grande rift is a complex north-striking half graben that is separated from adjacent segments by an accommodation or transfer zone, across which stratal tilts reverse. The accommodation zones are crustal flaws (fault zones or poorly defined structural lineaments) which in places exploited Laramide and older zones of weakness and locally acted as a conduit for magma (e.g., Russell and Snelson, 1994).

This study explores the relationships between the direction of stratal tilt within each major normal-fault-bounded segment of the northern Rio Grande rift and the steep, thrust-faulted side of the Laramide uplift within which the segment lies. The evidence strongly suggests that the geometry of the Tertiary basins may be genetically linked to the symmetry of the older Laramide uplift. Three grabens of the northern Rio Grande rift, underlying the San Luis basin, the upper Arkansas River Valley, and the Blue River Valley (Fig. 1), support a model, based, in part, on ideas presented by Wise (1963); Scholten (1967); Royse et al. (1975); Schmidt et al. (1984); Kellogg et al. (1995), which explains how Laramide faults and uplifts controlled the placement and orientation of Neogene faulting and basin formation. This paper tests the applicability of the model, described in the next section, to the major structural features along and adjacent to various parts of the northern Rio Grande rift.

2. Basement uplifts and Neogene grabens: a possible genetic link

Deep seismic reflection profiles across several Laramide uplifts, such as the Wind River Mountains in Wyoming and the Manzano uplift in New Mexico, indicate that on at least one side listric thrusts, flattening at depth into the middle crust at about 15–16 km, bound the uplifts (Sharry et al., 1986; de Voogd et al., 1988; Russell and Snelson, 1994). The bounding thrusts commonly control the position of Tertiary normal faults by offering zones of weakness that can be exploited during crustal extension (Royse et al., 1975; Smith and Bruhn, 1984; Arabasz et al., 1992; Kellogg et al., 1995). Tertiary basin-bounding normal faults also appear to root into older thrusts in the southern Albuquerque basin (Russell and Snelson, 1994). Reiter et al. (1992) presented a quantitative, isostatic model for the reactivation of Laramide thrusts and the formation of half grabens by rotation of domino-style crustal blocks.

Southwestern Montana contains many excellent examples of Neogene extensional features that reactivate Laramide structures. At least four Neogene extensional valleys as wide as 20 km formed along the axial zones of large (as wide as 30 km) Laramide uplifts (Scholten, 1967). The thrusts define the east side of each uplifts and produce large basement overhangs above a footwall syncline in Paleozoic and Mesozoic rocks (e.g., Kellogg et al., 1995) (Fig. 2A). According to a model for structural inversion (Schmidt and Dresser, 1984; Schmidt et al., 1984; Kellogg et al., 1995), the unsupported eastern side of a basement arch in Montana underwent rotational sagging into the underlying or adjacent basin sediments, thereby producing extension, fracturing, and possibly normal faulting along the crestal zone of the arched basement block. Similar crestal normal faulting ('keystone faulting') was recognized long ago in the basement uplift of the Owl Creek Mountains, Wyoming (Wise, 1963). The fractures were later exploited during Tertiary crustal-wide extension, resulting in large-scale collapse and development of a basin along the axial part of the Laramide arch (Fig. 2B). ‘Perched basement wedges’ (Lageson, 1989), bounded on one side by Laramide-age thrusts and on the other side by Neogene normal faults, typically result from this process (Fig. 2C). In most cases, strata in the basins adjacent to the basement wedge dip toward both the major valley-bounding normal faults and older uplift-bounding thrusts.

The idea that normal faults commonly exploit older thrust is well established. For example, seismic studies across the Idaho–Wyoming thrust belt show that Neogene normal faults commonly sole into underlying thrust ramps (Royse et al., 1975). Field re-
relationships also demonstrate that some normal faults adjacent to basins in southwestern Montana sole into older thrust surfaces (Kellogg et al., 1995); similar relationships have been mapped in southeastern Idaho (Kellogg, 1992).

The mechanisms by which Laramide (and earlier) crustal shortening controlled Neogene extension are complicated and still poorly understood, and the model outlined here for listric thrusts and normal faults, although favored by the author, is one of several that have been proposed. Seismic evidence for listric Laramide thrusts and Neogene normal faults commonly is equivocal and some researchers suggest that basin-bounding normal faults may be planar to at least 15 km depth (Dozer and Smith, 1985) or steepen with depth and root into thrusts that also steepen downward (e.g., Sales, 1983). A new school of thought propose that north-striking Laramide faults in New Mexico and southern Colorado have a large component of dextral slip and a relatively small component of reverse slip (e.g., Bauer and Raiser, 1995; Wawrzyniec and Geissman 1995). For example, movement along one of the major faults bounding the east side of the southernmost San Juan–San Luis uplift (the Picuris–Pecos fault in the southernmost Sangre de Cristo Mountains near Santa Fe, New Mexico) has an ancestry that is as old as Proterozoic and an inferred 37 km of mostly Laramide dextral strike-slip motion (Bauer and Raiser, 1995); the fault is viewed as a positive flower structure that steepens downward to an essentially vertical attitude. If one accepts that the Laramide orogeny was marked by significant crustal shortening, however, then it is difficult to reconcile such shortening along downward-steepening faults. In addition, the inferred, predominantly strike-slip, non-listric geometry inferred for the Picuris–Pecos fault precludes exploitation of the fault by Neogene normal faults along the east side of the adjacent rift basin (Española Basin).
3. Geologic setting of the northern Rio Grande rift

Laramide crustal contraction and resultant uplift along the San Juan–San Luis arch began about 70 Ma (late Campanian) and created a highland that shed clastic detritus into bounding basins until the Late Eocene (Tweto, 1975), at which time a widespread erosion surface extended across most of Colorado (Epin and Chapin, 1975). Rio Grande rifting began shortly after 29 Ma (Tweto, 1979; McIntosh et al., 1992) and was marked by a change in volcanism from the intermediate compositions that characterized the widespread Oligocene volcanic fields (Steven, 1975) to bimodal basalt–rhyolite (mostly basalt) volcanism that characterizes the Rio Grande rift (Lipman and Mehnert, 1975). This fundamental change in volcanic style coincides with a change throughout the western United States from subduction-driven to extension-driven tectonic regimes in the Late Oligocene to Early Miocene (Christiansen and Lipman, 1972). A subsequent period of rapid faulting and extension in New Mexico and the San Luis basin of Colorado culminated in the Middle to Late Miocene (Chapin and Cather, 1994) and was accompanied or closely followed by voluminous basaltic volcanism between 3 and 8 Ma (Seager and Morgan, 1979).

Despite paleobotanical evidence that suggests that the Rocky Mountains have been topographically high since the Eocene (e.g., Gregory and Chase, 1994), other studies indicate that the rise of the modern Rocky Mountains was accompanied by a period of rapid faulting and extension in the Middle to Late Miocene (Chapin and Cather, 1994; Steven et al., 1997). Such uplift is consistent with apatite fission-track ages which indicate that the Sawatch and Sangre de Cristo ranges underwent significant uplift since about 20 Ma (Bryant and Naeser, 1980; Lindsey et al., 1986; Kelley et al., 1992).

3.1. The San Luis basin and adjacent uplifts

The San Luis basin extends from about 10 km south of Salida, Colorado, to about 80 km south of the Colorado–New Mexico border; only the Colorado portion of the basin is shown in Fig. 1. The basin is bordered on the west by a gently east-dip-
Laramide movement, with a right-lateral component along the north-striking part of the thrust system and a left-lateral component on the Kerber Creek thrust.

Sales (1983) suggested that the Tertiary normal faults along the Sangre de Cristo fault system merge at depth with the older thrusts, which generally steepen downward, a geometry based, in part, on laboratory modeling experiments. Deep seismic reflection studies resolve neither the orientation nor the curvature of the Sangre de Cristo fault system, although modeling suggests that the most likely orientation is about 60° to a depth of about 6 km (Kluth and Schaftenaar, 1994). Using this angle, a graphical method reported by Kluth and Schaftenaar (1994) indicates that the depth of detachment (flattening) is at about 16 km, the depth of the brittle-ductile transition zone estimated from heat-flow studies.

3.2. Villa Grove accommodation zone

VanAlstine (1968) suggested that the upper Arkansas River graben is structurally continuous with the San Luis basin, but westward stratal dip of Miocene rocks and the down-to-the-east normal fault along the west side of the upper Arkansas River graben dies out just north of Poncha Pass (Fig. 1), the topographic gap between the San Luis basin and the upper Arkansas River graben. The area surrounding Poncha Pass is complexly faulted and contains Proterozoic rocks that are exposed across virtually
the entire rift. South of Poncha Pass, stratal dip is east and major normal faulting is on the east side of the San Luis basin, along the Sangre de Cristo fault zone (compare Fig. 3A and 3B). The reversal in stratal dip across Poncha Pass is about 20 km north of the Villa Grove accommodation zone (VGAZ in Fig. 1) of Chapin and Cather (1994), a proposed northeast-trending crustal-scale structural lineament or zone of weakness across which stratal tilt supposedly reverses. Despite the 20-km relocation in the present study, the name ‘Villa Grove accommodation zone’ is retained.

A Laramide transition zone between the strongly west-directed Sawatch uplift and the east-directed San Luis uplift is approximately coincident with the Villa Grove accommodation zone. The northern limit of east-directed thrusts adjacent to the San Luis basin is about 15 km south of the accommodation zone, at the position of the Kerber Creek thrust. The southern limit of west-directed thrusting on the west side of the Sawatch uplift is not clear, but appears to be at about the same latitude as the Villa Grove accommodation zone.

3.3. The Sawatch uplift

The Laramide Sawatch uplift (Sawatch anticline of Tweto, 1975) is a large north-plunging arch of Proterozoic rock, the east flank of which, from the crest of the Mosquito Range eastward into South Park. is overlain by relatively undeformed, mostly flat-lying late Paleozoic and Mesozoic rocks (Tweto, 1979). In contrast, most of the west side of the uplift contains a complex of steep, discontinuous faults which, near Aspen, is called the Castle Creek fault zone (Bryant, 1979). Total displacement across the fault zone is about 3600–4300 m, and beds adjacent to the zone dip steeply west or are overturned. Faults dip both east and west and are characteristically discontinuous along strike, although many of the faults are clearly east-dipping thrust or reverse faults (Spurr, 1898; Bryant, 1979). Tweto et al. (1978) interpreted most of the faults along the west side of the Sawatch uplift to be normal faults, including those of the Castle Creek fault zone. However, intrusive relationships with the fault zone indicate that the faults formed during the Laramide orogeny (Bryant, 1979), suggesting that the zone is contractional rather than extensional. Recent mapping along the west side of the Sawatch uplift, north of the Castle Creek fault zone, has demonstrated the contractional character of the west margin of the uplift (Wallace and Blaskowski, 1989). In addition, the steeply dipping to overturned beds adjoining the uplift on the west characterize a large footwall syncline structure, similar to those commonly mapped adjacent to and beneath Laramide basement-involved thrusts (e.g., Kellogg et al., 1995). Inferred northward migration of the Colorado Plateau may have added a component of dextral strike slip along the fault zone (Wawrzynciecz and Geissman, 1995), although supportive data are inconclusive.

Numerous Laramide and younger, mostly felsic plutons that lie along the northeast-trending Colorado mineral belt intrude the Sawatch uplift. A large gravity low coincides with the belt and indicates that the plutons form the apophyses of a large, mostly hidden plutonic complex (Tweto, 1975).

The northwest-striking, southwest-directed Elk Range thrust crops out west of the Castle Creek fault zone (Fig. 1). The thrust, largely a bedding-plane structure in Permian and Pennsylvanian rocks, cuts rocks as young as Cretaceous (Bryant, 1979); total transport distance is at least 5–6 km. Bryant (1979) suggested that the Late Cretaceous or Early Paleocene Elk Range thrust formed by gravity sliding off the Sawatch uplift. Alternatively, although the Elk Range thrust is oblique to the west margin of the Sawatch uplift, it is geometrically permissible that the thrust roots beneath the large west-directed basement block that forms the Sawatch uplift (Fig. 3B). To the northwest, contraction along the Elk Range is transferred to a west-to-southwest-directed blind thrust system that underlies the Grand Hogback monocline. The blind thrust is likely an out-of-basin thrust involving a basement wedge (Perry and Grout, 1988).

3.4. The upper Arkansas River graben

The north-striking upper Arkansas River Valley occupies the northernmost major graben in the Rio Grande rift system and splits the east-central portion of the Sawatch uplift. Although complicated in detail, the graben contains a west-dipping basin-fill sequence (Upper Miocene and Lower Pliocene Dry
Union Formation) that is truncated on the west side by a large 'master' normal fault with at least 3000 m vertical offset (Knepper, 1976) (Fig. 3B). Resistivity and gravity data (Tweto and Case, 1972) also indicate that the bedrock surface beneath the Dry Union Formation near Buena Vista slopes steeply westward and is truncated by the large east-dipping normal fault (Tweto, 1978) (Fig. 3B).

The east side of the graben contains a number of down-to-the-west normal faults that step up almost to the crest of the Mosquito Range. Many of these faults have a Laramide ancestry, as shown by their relationship to dated Laramide intrusive rocks (Tweto, 1979). "These west-dipping faults originated as antithetic faults in the flank of the Laramide Sawatch anticline, and they were reactiivated in Neogene time to serve as elements of the upper Arkansas Valley graben structure." (Tweto, 1979, p. 44.)

3.5. The Gore and Front Range uplifts

The Gore Range is a narrow, rugged, uplifted block of Proterozoic rock bounded on the west by the Gore fault and on the east by the Blue River normal fault (Fig. 1). The Blue River Valley follows a 5 to 9 km wide graben that is floored mostly by Upper Cretaceous shale (Tweto et al., 1978; Kellogg, 1997) and separates the Gore Range from the western side of the Front Range. The Williams Range thrust bounds the graben on the east and is a low-angle to nearly horizontal structure that probably steepens farther to the east under the Front Range block, where it presumably overlies basement rock (Fig. 3C). The Williams Range thrust defines the western structural boundary of the Front Range, which, on the east, is bounded by high-angle Laramide contractional faults (Fig. 1). Erslev (1993) suggested that the Williams Range thrust is a back thrust in an overall east-directed Laramide thrust system, which implies that that Front Range is completely detached.

The Gore fault has had a long geologic history, the details of which are somewhat controversial. It was active during Proterozoic, late Paleozoic, and Late Cretaceous–early Tertiary time (Tweto, 1979) and approximately defines the eastern structural margin of the late Paleozoic central Colorado trough (Fig. 3C). This trough collected a thick, eastward-thinning clastic assemblage, banked against the eastern margin of the trough and shed westward from the Ancestral Front Range uplift (DeVoto, 1980). The uplift began during early Pennsylvanian time and created a region that remained topographically high until Late Jurassic time; sedimentary rocks older than Jurassic are missing from an area that includes most of the present Front Range, Gore Range, Park Range, Middle Park, and the northern Blue River graben (Tweto, 1975). Tweto et al. (1970) interpreted the Gore fault, on the west side of the Gore Range, as a normal fault, but a more recent interpretation suggests that it represents major Pennsylvanian and Early Permian west-directed contractional faulting that accompanied uplift of the Ancestral Front Range (Ye et al., 1996). Evidence is lacking for major Laramide movement along the Gore fault (Tweto and Lovering, 1977), although Snyder (1980) documented major west-directed Laramide thrusting along the western margin of the Park Range (northern continuation of the Gore Range). The complex pattern of faulting and the steep to overturned eastern margin of the central Colorado trough mirrors that on the west side of the Sawatch uplift, all of which supports a model for both late Proterozoic and Laramide contractional movement along the Gore fault.

3.6. The Blue River graben and western Middle Park

Although deep sediment-filled basins of the Rio Grande rift end at the northern end of the upper Arkansas River graben, major Neogene faults related to Rio Grande rifting extend for a considerable distance farther north. The Neogene Blue River normal fault, along the east side of the Gore Range (Fig. 3C), is a major element of the Rio Grande rift system that underwent several thousand meters of down-to-the-east movement, probably no later than the Pliocene (West, 1978). In addition, numerous north-striking normal faults in the Blue River graben are almost entirely east-dipping (Kellogg, 1997), indicating that the Blue River graben is a west-tilted structure. The valley, however, contains little Neogene basin-fill deposits, indicating that the drainage basin formed by the graben was neither structurally deep nor closed to the north, where the Blue River empties into the Colorado River near Kremmling (Fig. 1).

The western Middle Park basin (Fig. 1) also forms a west-tilted Neogene half graben, filled by
Miocene basin-fill deposits of the Troublesome Formation, a sequence of tuffaceous siltstones, sandstones, and conglomerates (Izett, 1975). On the west, the down-to-the-east Antelope Pass normal fault bounds the Middle Park basin and approximately follows the trace of the Williams Range thrust.

1. Discussion

At several localities along the northern Rio Grande rift there appears to be an association between Neogene normal faults and Laramide thrust faults, strongly suggesting that the two types of faults are genetically linked. The model presented here for the development of Tertiary basins along the crests of earlier thrust-bounded uplifts explains this association: the San Luis basin and its relationship with the San Juan–San Luis uplift is an excellent example (Fig. 3A). In addition, the near coincidence of the Villa Grove accommodation zone, where stratal tilt reverses direction, and the boundary between the Sawatch uplift and the San Juan–San Luis uplift, where thrust-transport direction also switches direction, does not seem merely fortuitous. The Villa Grove accommodation zone appears to exploit a pre-existing zone of crustal weakness that is at least as old as Laramide. It is worth noting, although not discussed in this paper, that similar structural precursors may have also existed for other accommodation zones (the Embudo, Santa Ana, Tijeras, and Socorro accommodation zones of Chapin and Cather, 1994) farther south along the Rio Grande rift (Russell and Snelson, 1994; S.M. Cather, written commun., 1998).

As applied to the Sawatch uplift, the model does not as clearly define the relationship between Laramide and Neogene structures as it does for the San Juan–San Luis uplift. About 30 km separates the west margin of the uplift and the upper Arkansas River graben, a distance considerably wider than other recognized perched basement wedges. The western margin of the Sawatch uplift is not universally interpreted as a contractional margin (e.g. Tweto et al., 1978), although evidence presented here strongly suggests that it is contractional. If true, faults along the west margin of the Sawatch uplift, possibly including the Elk Range thrust, represent the surface traces of a listric west-directed fault system that underlies the Sawatch uplift and accommodated Laramide crustal shortening, eastward tilting, and uplift. The Dry Union Formation in the upper Arkansas River graben dips toward both the master normal fault along the west side of the valley and the steep, thrust-faulted side of the Sawatch uplift (Fig. 3B).

The upper Arkansas River graben lies astride the central part of the Sawatch uplift. The relatively large distance between the valley and the west side of the uplift, where the model would predict that the basement overhang would sag into the adjacent sedimentary basin, is difficult to reconcile. Possibly, arching and gravitational spreading (extension) concurrent with Laramide intrusive activity under the Sawatch uplift may have contributed to extensional strain as well as facilitated movement along thrusts, thereby permitting the wide 'perched basement wedge.'

A complicated relationship also exists between the Gore Range–Front Range uplift and the Blue River graben, but nonetheless indicates that the graben inherited its geometry from older contractional structures. The Gore fault, along the west side of the Gore Range, is not entirely a Laramide structure; indeed, most of the movement along the fault may be late Paleozoic in age. Nonetheless, the Blue River graben tilts strongly west and sits above a west-directed thrust system, suggesting that the normal faults sole just as easily into thrusts that are partly Paleozoic in age as they do into thrusts that are exclusively Laramide. Irrespective of the age of the Gore fault, westward tilting of the southern Blue River graben and western Middle Park basin was accommodated along normal faults, interpreted as listric, that sole into the thrust (Fig. 3C). The Gore Range represents a 'perched basement wedge' bounded on the west by the Gore thrust or reverse fault and on the east by the Blue River normal fault. Similarly, westward rotation of the western Middle Park basin resulted by movement along the Antelope Pass normal fault, which may merge at depth with the Gore thrust.

East-directed, commonly blind Laramide thrusts that probably also have a late Paleozoic ancestry also bound the east margin of the Front Range uplift, although a Neogene rift valley associated with this margin did not form. Apparently, crustal extension
coeval with Rio Grande rifting did not extend to the east margin of the Front Range uplift.

5. Conclusions

This study documents a style of deformation that is characteristic, not only of the northern Rio Grande rift, but also of large parts of the Rocky Mountain region of North America. Future studies may judge whether there are analogues throughout the world. The major conclusions of this study are summarized as follows.

(1) An empirical association between the sense of asymmetry of several basins of the northern Rio Grande rift and the sense of asymmetry of the Laramide uplift on which the rift basin sits suggests a genetic link. The down-rotated side of each basin appears on the same side as the thrust-faulted side of the uplift. The thrust faults that bound the uplifts are interpreted to be listric and flatten in the middle crust at about 15–16 km.

(2) The Villa Grove accommodation zone bounds the down-to-the-east San Luis basin portion of the Rio Grande rift and the down-to-the-west upper Arkansas River graben, and also appears to define a zone that separates the east-vergent San Juan–San Luis arch from the west-vergent Sawatch uplift.

(3) Fault relationships on the west side of the Sawatch uplift suggest that a west-directed Laramide thrust, defined, in part, by the trace of the Castle Creek fault zone, underlies the uplift. The upper Arkansas River graben lies astride the Sawatch uplift and tilts west into a large ‘master’ normal fault.

(4) The Blue River graben and western Middle Park basin lie astride the Front Range–Gore Range uplift and tilt to the west against large east-facing normal faults. Major late Paleozoic movement along the thrust on the west side of the Gore Range, associated with uplift of the ancestral Rocky Mountains, reactivated during the Laramide.

(5) The above relationships suggest a model, similar to one first summarized by Schmidt et al. (1984) and expanded upon by Kellogg et al. (1995), in which rotational sag of a thrust-bounded basement overhang into an adjacent sedimentary basin produced zones of extension in the arched basement block. During subsequent crustal extension, the already-extended zones in the arched central part of the fault blocks underwent gravitational collapse, producing an asymmetrical graben along the axial part of the arch. The master normal fault controlling the downthrown side of the graben roots into the older thrust. The resultant ‘perched basement wedge’ is bounded on one side by a thrust and on the other side by a younger normal fault.

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