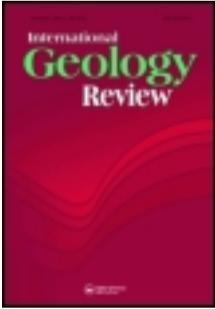


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An Yin^a & Raymond V. Ingersoll^a

^a Department of Earth and Space Sciences, University of California,
Los Angeles, California, 90095-1567

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A Model for Evolution of Laramide Axial Basins in the Southern Rocky Mountains, U.S.A.

AN YIN AND RAYMOND V. INGERSOLL

Department of Earth and Space Sciences, University of California, Los Angeles, California 90095-1567

Abstract

The structural, stratigraphic, and sedimentologic development of Laramide axial basins of the southern Rocky Mountains is inconsistent with previous models relating them to transpressional tectonics. Axial basins are better explained as broad synclinal troughs in the hanging walls of large pop-up structures, in contrast to perimeter and ponded basins formed in the footwalls of these same structures. Laramide faults in the southern Rocky Mountains can be divided into the E-dipping Park Range thrust system and the W-dipping Sangre de Cristo thrust system. The W-dipping Front Range fault is the backthrust of the Park Range system, and the E-dipping Nacimiento fault is the back-thrust of the Sangre de Cristo system. The broad synclinal troughs formed between these two pairs of oppositely verging thrust systems were the locations for sediment deposition in axial basins, as exemplified by the Galisteo–El Rito basin of northern New Mexico. The Eocene Galisteo and El Rito formations were deposited on a broad syncline of Phanerozoic strata with crystalline basement along the basin margins. Most sediment was derived from the northeast, north, and northwest, except near the NE-trending Tijeras-Cañoncito transfer zone along the southeast margin of the basin. Uplift of the Sangre de Cristo Range occurred first, followed by backthrusting to uplift the Sierra Nacimiento. This model explains Laramide uplifts and basins as the direct response to rapid NE-SW convergence between the North American and Farallon plates, without multiple reorientation of Laramide stress fields, and without major strike-slip along the eastern side of the Colorado Plateau.

Introduction

AN IMPORTANT RECORD of the latest Cretaceous through Eocene Laramide orogeny in the southern Rocky Mountains (United States) is preserved in syntectonic sedimentary basins. Dickinson et al. (1988) classified Laramide basins into perimeter, ponded, and axial types (Fig. 1), based on their architecture and structural settings. The structural origins of the first two types, with their associated basin-vergent thrusts, are well understood; their development has been related to flexural loading of footwalls due to thrusting of hanging walls. On the other hand, the structural setting of axial basins is controversial. Although Dickinson et al. (1988) accepted the suggestion by Chapin and Cather (1981) that axial basins originated by transpressional tectonics, we find this model to be inconsistent with both structural and sedimentological characteristics. In this paper, we review these characteristics and propose a model that relates axial basins to the development of broad synclinal troughs in the hanging walls of large pop-up structures (Yin and Ingersoll, 1993).

Geologic Constraints

Structural geology

The key to understanding the origin of axial basins is the structural history of the Laramide faults that bound them. Documenting this history requires knowledge of the kinematics of the faults, a topic that has been controversial. Two end-member models have been proposed: (1) the N-trending faults along the east side of the Colorado Plateau reflect transpressional tectonics (Chapin and Cather, 1981); and (2) they are thrusts produced by NE-SW compression (i.e., Kelley, 1955; Sales, 1968). The first model is based primarily on the fact that the Uinta Mountains experienced N-S shortening during the Laramide orogeny (e.g., Gries, 1983), apparently requiring northward relative movement of the Colorado Plateau. This argument is potentially flawed, however, because it implicitly assumes that deformation on the northern and eastern sides of the Plateau was produced by the interaction of two rigid blocks: the North American craton and the Colorado Plateau. Considering the presence of complex

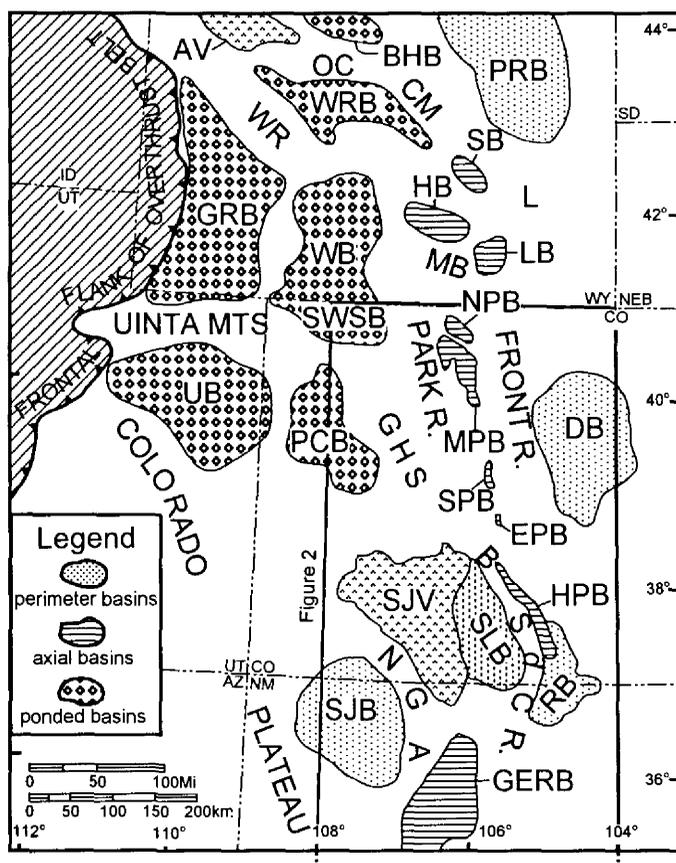


FIG. 1. Laramide basins, uplifts, and related features of southern Wyoming, Colorado, northern New Mexico, and surrounding regions (after Dickinson et al., 1988). Perimeter basins: PRB = Powder River; DB = Denver; RB = Raton; SJV = San Juan. Axial basins: SB = Shirley; HB = Hanna; LB = Laramie; NPB = North Park; MPB = Middle Park; SPB = South Park; EPB = Echo Park; HPB = Huerfano Park (although actually a continuation of the perimeter Raton basin; see text); GERB = Galisteo-El Rito. The axial Monte Vista basin underlies the Neogene San Luis basin (SLB). Ponded basins: BHB = Big Horn; WRB = Wind River; GRB = Green River; WB = Washakie; SWSB = Sand Wash sub-basin; UB = Uinta; PCB = Piceance Creek. Mid-Tertiary volcanic fields: AV = Absaroka; SJV = San Juan. Uplifts: OC = Owl Creek; WR = Wind River; CM = Casper Mountain; L = Laramie; MB = Medicine Bow; GHS = Grand Hogback-Sawatch; NGA = Nacimiento-Gallina-Archuleta; BSdCR = Brazos-Sangre de Cristo Range. Also shown are Park Range, Front Range, Colorado Plateau, and frontal flank of overthrust belt (primarily Cretaceous). Northern part of Figure 2 is outlined by heavy lines.

Laramide faults immediately north of the Plateau, Yin et al. (1992) suggested that E-W compression along the Park Range and Front Range, NE-SW compression along the Laramie and Medicine Bow Mountains, and N-S shortening across the Uinta Mountains could have resulted from the interaction of several blocks, based on the integration of slip vectors across individual Laramide faults. This interpretation is consistent with recent kinematic studies along the Cheyenne belt in the Laramie

basin, where NE-striking strike-slip faults are linked with NW-striking thrusts (Stone, 1995), indicating that range-bounding faults are thrusts in the Laramie and Medicine Bow Mountains immediately to the east and south. Also, Paylor and Yin (1993) and Molzer and Erslev (1995) documented oblique convergence during NE-SW Laramide compression along the E-W Owl Creek and Casper Mountain arches in central Wyoming. Furthermore, Erslev et al. (1996) demonstrated that Laramide

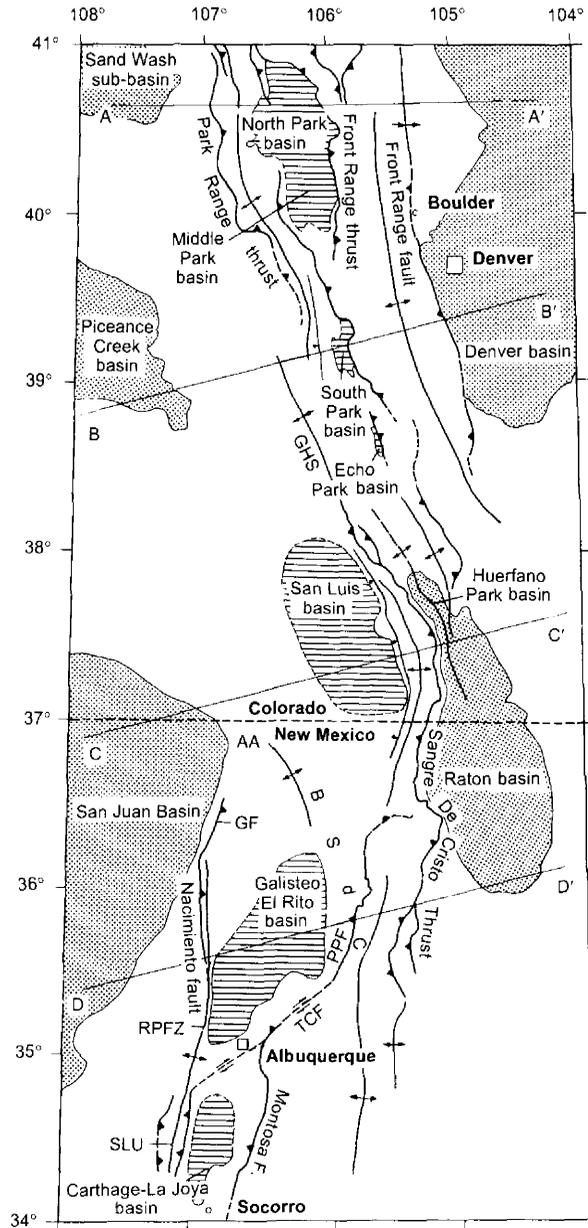


FIG. 2. Tectonic map (modified from Tweto, 1978, and Woodward et al., 1978) of the southern Rocky Mountains in Colorado and northern New Mexico, showing major thrusts and basins and locations of cross-sections (see Fig. 3). Abbreviations: GHS = Grand Hogback-Sawatch uplift; AA = Archuleta arch; GF = Gallina fault; BSdC = Brazos-Sangre de Cristo uplift; PPF = Picuris-Pecos fault; RPFZ = Rio Puerco fault zone; TCF = Tijeras-Cañoncito fault; SLU = Sierra-Ladron uplift. Only a few Neogene normal faults are shown.

faults in the Front Range, Wet Mountains, and Sangre de Cristo Range all experienced a single phase of $N75^{\circ}E-S75^{\circ}W$ compression.

Based on this premise, regional compilation of geologic maps, and sedimentologic arguments, we divide the Laramide faults in the

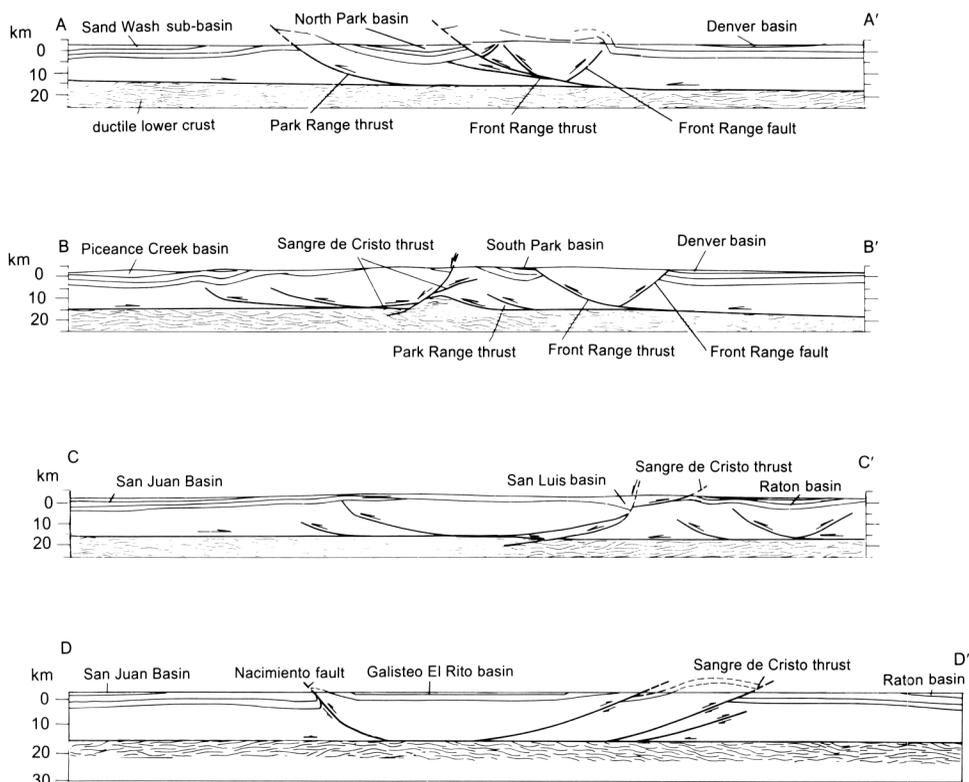


FIG. 3. Structural cross-sections showing positions of Laramide basins, thrusts, uplifts, and a few major Neogene normal faults. See Figure 2 for locations.

southern Rocky Mountains into two large thrust systems: the E-dipping Park Range thrust system to the north and the W-dipping Sangre de Cristo thrust system to the south (Figs. 2 and 3). The two fault systems north of the San Luis basin form an overlapping transfer zone. The Front Range fault (with its minor shortening) is the backthrust of the Park Range thrust. Similarly, the Nacimiento fault is the backthrust of the Sangre de Cristo thrust. Within this structural framework, the tectonic settings of the major Laramide basins are clear. The Sand Wash sub-basin and Piceance Creek basin are the foreland basins of the Park Range thrust, whereas the Raton basin is the foreland basin of the Sangre de Cristo thrust. The broad, shallow Denver and San Juan basins are located at broad asymmetric synclinal troughs in the footwalls of the backthrusts. The axial basins of Dickinson et al. (1988) are all located between the main thrusts and their backthrusts. It is this characteristic structural setting of the axial

basins that produces their unique stratigraphic and sedimentological characteristics, as discussed below.

Although this hypothesis needs to be tested, we assume that the major Laramide thrusts in the southern Rocky Mountains soled into a ductile shear zone in the middle crust. This assumption is based on the following postulates: (1) the inferred rheology for the continental lithosphere consists of a weak and plastic lower crust (e.g., Chen and Molnar, 1983); and (2) intracontinental deformation, both in extension and contraction, may be characterized by detachment zones at mid-crustal levels, as suggested by Burchfiel et al. (1989).

Structural setting of sedimentary basins

Chapin and Cather (1981) used the Echo Park basin (Fig. 1) as the type example for what Dickinson et al. (1988) later named axial basins of the central and southern Rocky Mountains. Utilizing limited (primarily subsurface) data regarding the Echo Park basin, Chapin and

Cather (1981) attempted to demonstrate that the basin primarily resulted from Laramide transpressional deformation. We find their arguments unconvincing in detail for the basin itself, as well as unconvincing by comparison to known transpressional basins (e.g., Ridge basin of southern California; Crowell, 1982). Application of criteria for the recognition of strike-slip-related basins (e.g., Reading, 1980; Christie-Blick and Biddle, 1985; Nilsen and Sylvester, 1995) to Echo Park-type basins results in clear negation of significant strike-slip as a basin-forming process. For example, *none* of the following characteristics has been demonstrated: discordance of paleogeography or stratal thickness, mismatch between source rocks and alluvial fans, significant unconformities of the same age as adjoining thick syntectonic strata, extreme lateral facies variations, simultaneous extensional and compressional tectonics, or major strike-slip offsets of Laramide age (i.e., Reading, 1980).

In addition, we find the characteristics of the Echo Park basin to be distinctly different from those of the Galisteo-El Rito (GER) and other axial basins (discussed below). The structural setting of the Echo Park basin is similar to that of the Huerfano Park basin; both the Echo Park and the Huerfano Park basins are more appropriately described as perimeter basins, northeast of the Sangre de Cristo thrust belt, although late-stage basement deformation renders their relations less clear than for the contiguous Raton perimeter basin. Laramide axial basins developed above hanging-wall blocks, in contrast to perimeter and ponded basins formed on footwall blocks (e.g., Dickinson et al., 1988).

Chapin and Cather (1981), Chapin (1983), Laughlin (1991), and Karlstrom and Daniel (1993) all proposed major (greater than 1 km) N-S right slip along the trend of the modern Rio Grande rift during Laramide time. In contrast, none of the criteria for recognition of major strike-slip deformation (e.g., Reading, 1980; Christie-Blick and Biddle, 1985; Nilsen and Sylvester, 1995) can be applied successfully to any of the Laramide axial basins; Chapin and Cather (1981) did not even apply these criteria to the Echo Park basin, their type "wrench" basin. Right-slip offset of 100 to 170 km along the Rio Grande trend has been proposed, based on offset Precambrian magnetic anomalies (Chapin, 1983) and basement features (Laugh-

lin, 1991; Karlstrom and Daniel, 1993). We do not contest the possible dextral offset of Precambrian features, but we do question whether significant offset occurred during Laramide deformation (also see Woodward et al., 1997). Some dextral offset may have occurred during the late Paleozoic Ancestral Rocky Mountain orogeny (Kluth, 1986), although no significant offsets of this age have been demonstrated; basin and provenance evolution during the late Paleozoic is more consistent with predominantly orthogonal compressional deformation (Miller et al., 1963; Soegaard and Caldwell, 1990; Devaney and Ingersoll, 1993). The only plausible age for significant dextral slip along N-trending faults in northern New Mexico (e.g., Picuris-Pecos fault) is Proterozoic (Miller et al., 1963). Woodward (1994) summarized evidence against significant Laramide dextral offset along the western side of the Nacimiento uplift.

The Laramide compressional direction is identified by the northeast trend of the Tijeras-Cañoncito (TC) fault zone between the Montosa and Sangre de Cristo frontal thrust zones (Fig. 2). Lisenbee et al. (1979) documented the anastomosing nature of this vertical fault zone, which in a complex manner connects the northwest boundary of the Carthage-La Joya basin with the southeast boundary of the GER basin. Of all exposed faults in northern New Mexico, the TC fault best satisfies criteria for recognition of strike-slip faults (e.g., Reading, 1980; Christie-Blick and Biddle, 1985; Nilsen and Sylvester, 1995). On the other hand, magnitude and timing of displacement along the TC fault zone are difficult to constrain; Lisenbee et al. (1979, p. 95) concluded that some motion occurred during the Precambrian and late Paleozoic, but that "post-Cretaceous movement is responsible for most of the structure."

The regional orientation of maximum compression during Laramide deformation in New Mexico was roughly parallel to the TC fault zone (NE or NNE). This interpretation is consistent with geometric characteristics of the Rio Puerco fault zone (Slack and Campbell, 1976), the NNE-striking Gallina fault at the north end of the Nacimiento uplift (Woodward et al., 1992), and the en-echelon NNW-trending folds of the southeastern San Juan Basin (Baltz, 1967). Furthermore, the NNE-striking right-slip faults of the Pecos fault zone (Kelley, 1971)

and the NW- and WNW-trending Laramide uplifts of southern New Mexico (Seager and Mack, 1986) are consistent with this compression direction. Locations and orientations of many fault zones may have been determined by reactivation of late Paleozoic and Precambrian structures of diverse orientations, so that strain partitioning among faults was common (e.g., Varga, 1993).

Sedimentology

The best exposed and most studied of the Laramide axial basins is the Galisteo-El Rito (GER) basin of northern New Mexico (Figs. 1 and 2) (Stearns, 1943; Baltz, 1978; Gorham and Ingersoll, 1979; Logsdon, 1981; Ingersoll et al., 1990; Cather, 1992; Abbott et al., 1995). The GER basin is bounded on the northeast by the Brazos-Sangre de Cristo (BSdC) uplift, on the northwest by the Nacimiento-Gallina-Archuleta (NGA) uplift, on the southwest by the Rio Puerco fault zone and the Lucero uplift, and on the southeast by the TC fault zone (Fig. 2).

Key sedimentologic observations regarding the El Rito and Galisteo formations include the following (Gorham and Ingersoll, 1979; Logsdon, 1981):

1. All facies are alluvial or fluvial, with subordinate floodplain and lacustrine(?) deposits.

2. Paleocurrents are strongly southward, with general centripetal patterns along basin borders. Lower Galisteo strata were derived from the northeast (BSdC source), whereas the remainder of the Galisteo had multiple sources, including the NGA uplift.

3. Conglomerate and sandstone provenance consisted of Precambrian crystalline basement and Carboniferous through Cretaceous sedimentary strata; volcanic and volcanoclastic components are absent.

4. Strata rest disconformably on Cretaceous strata near the deepest part of the basin, with angular unconformity on Permian through Cretaceous strata along the northwestern basin margin, and nonconformably on Precambrian basement along the southwestern edge of the BSdC uplift (Baltz, 1978; Kelley, 1978; Gorham and Ingersoll, 1979; Logsdon, 1981). Thus, the GER basin was deposited above a broad syncline of Phanerozoic strata, with crystalline basement along the basin margins.

5. Strata thin to the northwest, north, and northeast; the thickest measured section is 1295 m of primarily fluvial/alluvial strata in the southern Hagan basin, adjacent to the TC fault zone (Gorham and Ingersoll, 1979).

Cather (1992, Fig. 7) summarized surface and subsurface data on stratal thickness of the Galisteo and El Rito formations, and provided paleogeographic and paleotectonic reconstructions. Our structural interpretation and reconstruction contrast markedly (compare his Figs. 9 and 10 to our Figs. 2 and 3). Because our model is based primarily on characteristics of the GER basin, we present a detailed discussion of how our interpretation differs from that of Cather (1992, p. 109), keyed to the four "modifications to the Tertiary history of north-central New Mexico" he proposed.

1. We see no compelling evidence for reverse faulting along the Pajarito fault zone (presently a normal fault along the east side of the Jemez volcanic field, which covers the west-central GER basin). Cather's primary evidence for a "Pajarito uplift" is the presence of basement clasts up to 50 cm in diameter, even though paleocurrents for this unit run southward, parallel to his hypothesized uplift. In contradiction to Cather's hypothesis is the presence of "maximum diameters of 3 feet" (about 90 cm) for clasts in the Hagan basin (Stearns, 1943, p. 307), which Cather's paleogeographic map (and ours) puts ~30 km downstream from Cather's study area. Characteristics of the Galisteo Formation at St. Peter's Dome (near the Pajarito fault) are similar to those of the El Rito Formation formed along the western side of the Brazos-Sangre de Cristo uplift, as described by Logsdon (1981); no "Pajarito uplift" is needed. The nonvolcanoclastic strata at Arroyo Hondo, similarly, can be interpreted as typical El Rito-Galisteo alluvial deposits preserved along the western edge of the BSdC uplift.

2. We know of no evidence that the TC fault zone was a releasing bend. In fact, Cather's Figure 9 shows "late Laramide signal" parallel to the TC fault, an interpretation consistent with our model. We interpret the TC fault zone as a transfer zone between the slightly transpressional Montosa fault and the highly compressional frontal thrusts of the Sangre de Cristo uplift (Fig. 2). As such, the TC fault zone may have been either transpressional or trans-

tensional, or possibly both (see Lisenbee et al., 1979).

3. We consider the "development of a flexural hinge" and the presence of the "Santa Ana accommodation zone" (north of Albuquerque and TCF in Fig. 2) as speculation with no supporting data. Southeastward thickening of the El Rito and Galisteo formations is irregular, with no clear break; in fact, Cather (1992) showed thicker Galisteo north of the "Santa Ana accommodation zone" at St. Peter's Dome than south of it, even though his primary criterion for locating it is the abrupt southward thickening of the Galisteo.

4. Because we see no evidence for the Pajarito uplift, we also see no evidence for its subsequent collapse. Normal movement on the Pajarito fault is demonstrably post-Bandelier Tuff (Pleistocene) (Smith et al., 1970). Evidence for Miocene movement is lacking; westward thickening of the Oligo-Miocene Abiquiu Formation within the Española basin probably results from the filling of residual Eocene (Laramide) topography (see Fig. 3 in Ingersoll et al., 1990). Greater normal displacement can be demonstrated along the eastern side of the Nacimiento uplift, which was the western boundary of the Española half-graben during the Miocene (Cavazza, 1989; Ingersoll et al., 1990; Ingersoll and Yin, 1993; Large and Ingersoll, 1997).

Other Laramide basins

In Colorado, the Piceance Creek basin formed in the foreland southwest of the Grand Hogback-Sawatch uplift (Fig. 1); the Denver basin formed in the foreland northeast of the Front Range uplift (see Chapin and Cather, 1981; Dickinson et al., 1988 for regional syntheses and additional references). We suggest that southwestward overthrusting occurred first along the Grand Hogback-Sawatch trend, followed by northeastward compression along the Front Range. If a broad axial basin analogous to the GER basin formed in central Colorado, then little evidence for this remains. We speculate that strata in the North, Middle, and South Park basins once were part of a broad synclinal basin (Hall, 1965), which subsequently experienced latest Laramide deformation and Neogene erosion. In contrast to the uniformly high elevations of northern and central Colorado, the Neogene Rio Grande rift of

southern Colorado to central New Mexico has formed along the trend of the Laramide axial basins, thus downdropping Laramide-age strata and preserving them beneath and along the margins of the rift basins.

In northern New Mexico and southern Colorado, structural events occurred in mirror image to those of northern and central Colorado. Northeastward overthrusting of the Sangre de Cristo Range formed the Raton foreland basin (Baltz, 1965), followed by southwestward compression of the NGA to form the San Juan Basin. Deposition of the Blanco basin and San Jose formations in the San Juan Basin occurred, in part, contemporaneously with deposition of the El Rito and Galisteo formations (Baltz, 1967; Smith et al., 1985; Brister, 1992; Smith, 1992; Brister and Chapin, 1994). San Jose fluvial systems transported detritus southward in the foreland west of the NGA uplift (Smith, 1992).

The Eocene Monte Vista basin underlies the Neogene San Luis basin in southern Colorado (Brister and Chapin, 1994; Brister and Gries, 1994). Little is known about this basin because it underlies Neogene rift strata (Santa Fe Group). Seismic and well studies (Brister and Gries, 1994) suggest that the "Blanco Basin formation" is similar in character to the Blanco Basin Formation along the northeastern side of the San Juan Basin. However, Late Eocene uplift of the Archuleta arch seems to have separated the two areas of deposition. Seismic line 1 of Brister and Gries (1994) clearly shows the "Blanco Basin formation" pinching out eastward against Precambrian basement of the Sangre de Cristo uplift. Thus, the overall setting of the Monte Vista basin is similar to that of the GER basin. Timing of uplift (early in the northeastern BSdC, later in the southwest Archuleta arch) also is similar to timing of development of the GER basin.

The tectonic setting of the Carthage-La Joya basin (south of the GER basin) (Fig. 2) was analogous to that of the GER basin, although the Carthage-La Joya basin was smaller and is less well exposed. The Carthage-La Joya is bordered on the east by the E-vergent Montosa uplift and on the west by the doubly vergent Sierra-Ladron uplift (Cabezas, 1991), from which the basin received sediment (Cather and Johnson, 1984). The TC fault zone separated

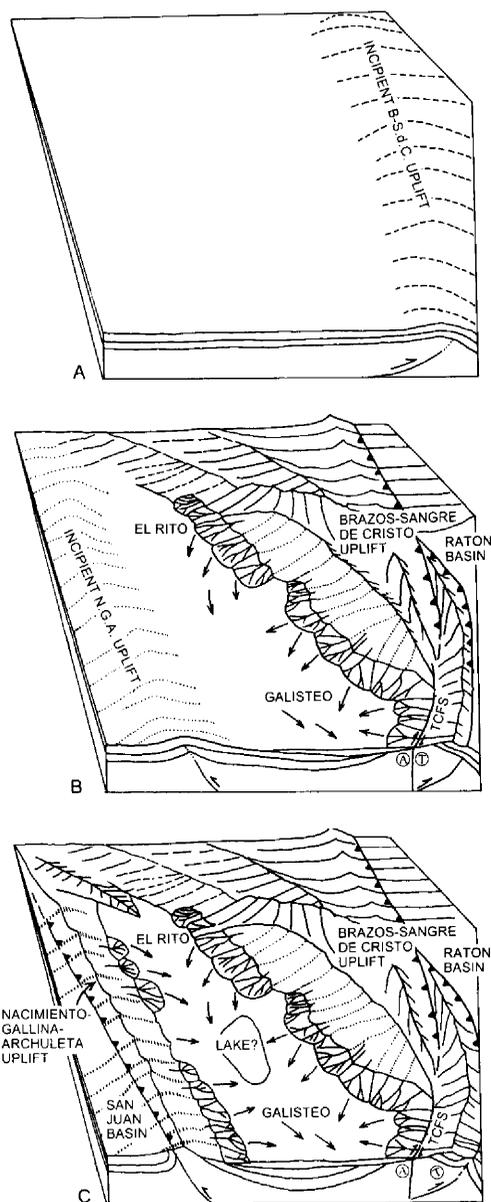


FIG. 4. Block diagrams showing structural and sedimentological evolution of northern New Mexico and southern Colorado during the Laramide orogeny, view to north (after Ingersoll et al., 1990). A. Initiation of movement along Sangre de Cristo thrust system (latest Cretaceous). B. Brazos-Sangre de Cristo uplift forms during thrusting, and provides sediment to the perimeter Raton basin and axial Galisteo-El Rito basin. Nacimiento-Gallina-Archuleta uplift begins to shed sediment into Galisteo-El Rito and San Juan basins as backthrusting begins (Paleocene-early Eocene). C. Galisteo-El Rito basin receives sediment from all directions in intermontane setting as thrusting and backthrusting continue. Raton and San Juan basins subside rapidly as a result of flexural loading as their margins deform (middle to late Eocene).

ment of the GER basin and its bounding uplifts. NE-SW compression was first expressed by basement-involved NE-vergent thrusting of the BSdC block, causing flexural subsidence of the Raton basin. Sediment derived from the BSdC uplift accumulated in the Raton basin most rapidly during the Paleocene (see Figs. 3 and 4 of Dickinson et al., 1988 for summary stratigraphic columns). High-angle, SW-vergent thrusting (possibly with a small transpressional component) began along the western side of the NGA uplift, resulting in subsidence of the San Juan foreland basin, which experienced maximum sedimentation rate in the early Eocene. The TC fault also was active as a dextral transfer zone. Sediment began accumulating as the Galisteo Formation in the deepest part of the synclinal trough as drainages adjusted to the changing topography; lower Eocene sediment came primarily from the BSdC uplift (Gorham and Ingersoll, 1979). Middle to upper Eocene sediment (El Rito and Galisteo formations) was derived from all directions, but primarily from the BSdC and NGA uplifts (Gorham and Ingersoll, 1979; Logsdon, 1981). Laramide compression, erosion, and sedimentation were terminated abruptly at the Eocene-Oligocene boundary as regional calc-alkaline volcanism exploded onto the landscape (Ingersoll et al., 1990).

Laramide axial basins of New Mexico and Colorado formed late during the Laramide orogeny (primarily Eocene) because finite compressional deformation over several million years was required to cause significant uplift in order to trap derived sediment within hanging-wall synclines. Sedimentation ceased soon after compressional deformation ended.

the deep GER basin to the northwest from the shallow Carthage-La Joya basin to the southeast (see Fig. 12 of Russell and Snelson, 1994).

The Model

Figure 4 integrates structural, stratigraphic, and sedimentologic constraints for develop-

Implications and Conclusions

Our model explains Laramide uplifts and basins as the direct response to rapid NE-SW convergence between the North American and Farallon plates (e.g., at 50 Ma of Fig. 8 of Engebretson et al., 1985; also see Coney, 1976; Bird, 1988; Brown, 1988). All observed structures and basins can be explained by this model without the need for multiple stages of Laramide stress orientations (e.g., Chapin and Cather, 1981; Gries, 1983).

The best modern analog for the Laramide orogeny is found in that part of the Andean orogenic system experiencing flat-slab subduction (Dickinson and Snyder, 1978; Jordan et al., 1983). In this setting, the Sierras Pampeanas and surrounding basement-cored uplifts in the Andean retroarc foreland are analogous to the Laramide uplifts. Compressional features are approximately perpendicular to the direction of modern plate convergence (Jordan and Allmendinger, 1986).

A more speculative modern analog for a similar structural setting to the Laramide orogen of the southern Rocky Mountains may be the Tian Shan in central Asia (e.g., Tapponnier and Molnar, 1979; Avouac et al., 1993). In the Tian Shan, two oppositely dipping thrust systems have formed large basement uplifts. Between the two thrust systems are numerous intermontane basins. Although the detailed structural setting is yet to be ascertained and the overall tectonic setting differs, we speculate that the general structural setting of these basins may be similar to that of Laramide axial basins described herein. Other modern and ancient analogs undoubtedly will be found after further research.

Acknowledgments

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