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Dextral Shear along the Eastern Margin of the Colorado Plateau: A Kinematic Link between Laramide Contraction and Rio Grande Rifting (Ca. 75–13 Ma)

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ABSTRACT

Kinematic data associated with both Laramide-age and -style and Rio Grande rift-related structures show that the latest Cretaceous to Neogene interaction between the Colorado Plateau and the North American craton was dominantly coupled with a component of dextral shear. Consistent with earlier studies, minor-fault data in this study yielded results of varied kinematics. Inverted to a common northeast-oriented hemisphere, the mean trend of kinematic shortening associated with Laramide-age structures is 056° ± 6°. Inverted to a common west-oriented hemisphere, the mean trend of kinematic extension associated with Neogene rifting is 300° ± 34°. The observed dispersion in these directions suggests multiphase deformation, particularly during rifting, along the margin of the plateau since the latest Cretaceous. These data were evaluated using a simple two-dimensional transcurrent kinematic model; assuming a minimal importance of strain partitioning, a mean trend of convergence between the Colorado Plateau and the North American craton was estimated to be 055° ± 5°. Subsequent Rio Grande rifting, which separated the plateau from the craton, was associated with a mean divergence trend of 307° ± 5.8°. Analysis of paleomagnetic data from Pennsylvanian to Triassic red beds along the eastern margin of the plateau and from rocks within the rift indicate clockwise rotations of uplifted blocks. Given the lack of regional strike-slip and dip-slip faults of common trends, the consistent clockwise rotations support an absence of strain partitioning. Correspondingly, for the north-south-trending eastern margin of the plateau, the apparently clockwise-rotated paleomagnetic data are consistent with dextral transpressive shear between the plateau and the craton. Previous data indicating counterclockwise rotations of crust within parts of the Española rift basin are, if reliable, consistent with dextral transtensive shear. Overall, the transition from latest Cretaceous/Early Cenozoic shortening to Cenozoic extension seems characterized by a quasi-continuous change from dextral transpressive to dextral transtensive deformation. This interpretation for the kinematic history of the eastern margin of the plateau demonstrates the importance of a dextral shear coupling between the craton and the Farallon plate system—a conclusion rarely implied by previous models of Cenozoic multistress field tectonics during deformation of the Cordilleran foreland.

Introduction

Along the eastern margin of the Colorado Plateau (fig. 1), latest Cretaceous to Early Tertiary (Laramide) contraction (ca. 75–35 Ma) and Rio Grande rift extension (ca. 29–0 Ma) represent a prolonged period of foreland deformation in the Cordillera of the western United States. Separated by an inferred period of tectonic quiescence, these events and their kinematics have been the subject of several tectonic models (e.g., Kelley 1982; Hamilton 1988; Chapin and Cather 1994). One recent model links earlier contraction to subsequent extension by several intermediate phases of mixed dextral and sinistral strike-slip faulting (Erslev 1999, 2001).

In this article, we evaluate the kinematic history of the eastern margin of the Colorado Plateau, recorded in minor-fault populations near the latest Cretaceous to Early Tertiary Laramide style and the Tertiary Rio Grande rift-related structures, to test

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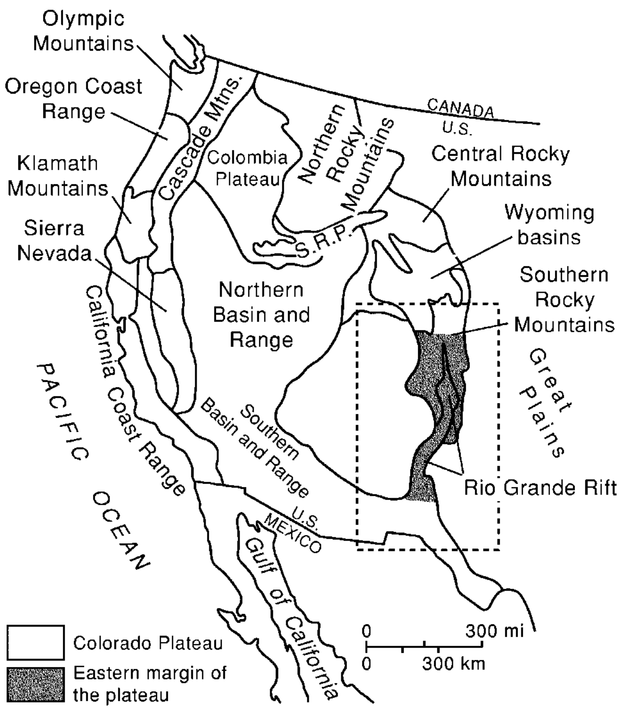

Figure 1. Generalized map of physiographic provinces of the Cordillera of the western United States. The dashed box is the region shown in figures 2, 3, and 5.

the following hypothesis. If the western margin of North America has experienced continuous dextral shear since the early Late Cretaceous (Engebretson et al. 1985) and the Colorado Plateau has acted as a quasi-independent crustal element with respect to the craton, then any far-field effects of plate interaction should be reflected in brittle structures along the plateau's eastern margin. Fault data should indicate a component of dextral shear during all phases of Laramide and younger interaction of the plateau with the craton.

Methods

We measured orientations of several populations of minor-fault planes of recognizable offset along the eastern margin of the Colorado Plateau. At each locality, we characterized minor-fault planes by measuring strike and dip of the plane and the rake of the fault plane lineation. Rake, measured from right-hand-rule strike, has a value between 0° and 180°. We determined sense of shear by observing offset markers or by brittle shear criteria (Petit 1987). Mean maximum infinitesimal elongation and shortening orientations (referred to as kinematic directions "s_1" and "s_3," respectively) from these populations were assigned to their respective regional structures, the Elk Range thrust, the Castle Creek structural zone of the Sawatch Range (Bryant 1966; Tweto 1977), the frontal thrust of the Sangre de Cristo Range (Lindsey 1998), and the Villa Grove transfer zone north of the San Luis Basin (Van Alstine 1974; Chapin and Cather 1994; fig. 2). We also studied faults that offset Tertiary intrusions, emplaced during and before the early stages of Rio Grande extension. With the exception of the intrusions, the kinematic data were collected from Precambrian crystalline and Cambrian to Tertiary sedimentary rocks. Following the techniques of Marrett and Allmendinger (1990), we calculated s_1 and s_3 directions for each minor fault (kinematic T and P axes, respectively). We determined mean orientations for s_1 and s_3 from each population using Bingham statistical methods.

To explore the possible influence of local block rotations on the kinematic data, we examined and summarized paleomagnetic data from several localities. We also obtained new paleomagnetic data from several thick sections of red beds, ranging in age from Late Pennsylvanian to Early Permian. For further details of these results, see Geissman and Mullally (1966), Lundahl and Geissman (1999), and Marshall and Geissman (2000). For each locality, independently oriented samples, as drilled cores, were collected from as many discrete beds (in hematite-cemented siltstones to fine- to medium-grained sandstones) as possible. Seven to 10 samples were typically collected from each bed. At least one specimen from each sample was progressively demagnetized by thermal demagnetization to about 680°C. We also treated selected samples using progressive chemical demagnetization. Alternating field demagnetization could not remove a sizable fraction of the natural remanent magnetization (NRM). We inspected demagnetization data using orthogonal demagnetization diagrams and stereographic projections and determined directions of magnetization that constituted sizable fractions of the NRM using principal components analysis (Kirschvink 1980) utilizing several demagnetization steps. Using Fisherian statistics, we estimated mean directions of magnetization for magnetization components common to most, if not all, samples at a specific site. We accepted site mean determinations when the α_{95} (cone of 95% confidence) parameter was <15°, when the number of independent samples was five or greater. The α_{95} parameter was usually <10° for sites that had more than five independent samples. We then analyzed location means for vertical axis rotations by

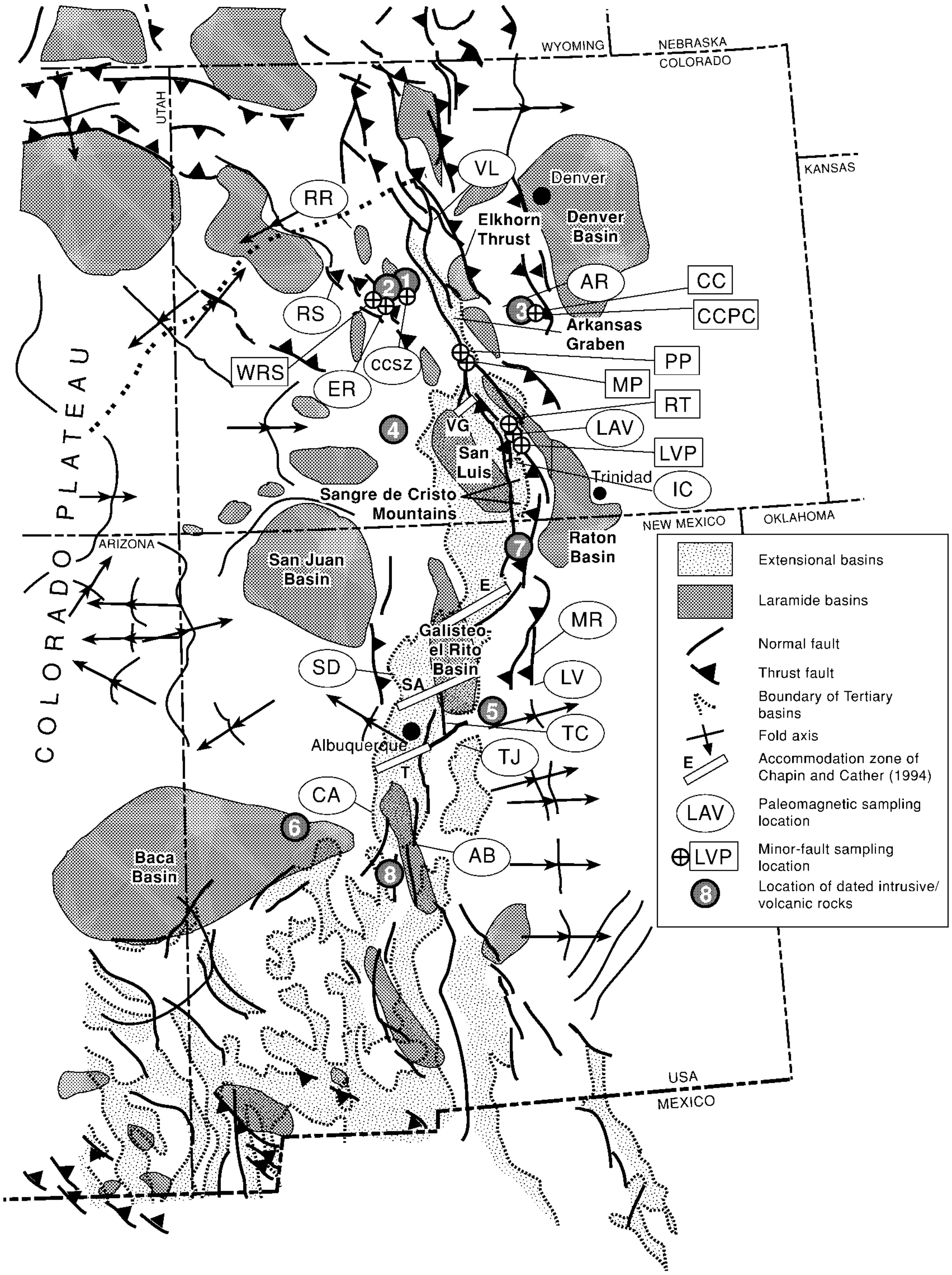

Figure 2. Generalized map of foreland uplifts and basins, and locations of paleomagnetic and minor-fault sampling sites (base map modified from Dickinson et al. 1988). Abbreviations for sites where minor-fault data and paleomagnetic samples were collected are given in tables 1 and 2, respectively. Abbreviations for accommodation zones: *VG* = Villa Grove; *E* = Embudo; *SA* = Santa Anna; *T* = Tijeras. Numbered locations: *1* = intrusions along the Castle Creek structural zone; *2* = White Rock stock; *3* = Cripple Creek diatreme; *4* = San Juan volcanic field; *5* = Oritz volcanic field; *6* = Mogollon-Datil volcanic field; *7* = Latir volcanic field; *8* = Socorro volcanic field (see Chapin and Cather 1994 for additional detail).

comparing the resolved mean directions to expected field directions to determine R and ΔR (95% error) values. The same analysis was applied to paleomagnetic data from previously published investigations.

We integrated the kinematic and paleomagnetic observations by considering them in a transcurrent reference frame. Of particular importance is a previously proposed quantitative relationship (Teyssier et al. 1995) between minor-fault strain data and relative plate motion. Our results support the hypothesis that, in regions where deformation occurs along oblique-slip structures, plate motion is not parallel to the related kinematic directions (maximum infinitesimal shortening and elongation). Moreover, the resulting synthesis of kinematic and paleomagnetic data strongly support the hypothesis that the eastern margin of the plateau has experienced a component of dextral shear during both contraction and subsequent extension of the Cordilleran foreland. The transcurrent frame thus provides an independent basis for estimating total northward translation of the plateau during latest Cretaceous through Cenozoic foreland deformation.

Kinematic Results

Fault orientation and offset data were collected from >700 individual fault planes from multiple outcrops at 10 localities along the eastern margin of the Colorado Plateau (fig. 3). Locality selection was largely based on the degree to which relative timing of deformation could be understood and, to a lesser degree, the proximity of these localities to rocks suitable for paleomagnetic analysis. Where applicable, the maximum age of deformation (table 1) was derived from crosscutting relations between minor-fault populations and intrusions of known age or between faults and strata within structurally controlled basins. Minimum ages of deformation are more equivocal; however, north of the Uinta Arch, Laramide-style deformation is thought to have ended in the Early Eocene (e.g., Dickinson and Snyder 1978; Mutschler et al. 1988). Contractional deformation along the eastern margin of the Colorado Plateau remains poorly constrained and may have continued into to the earliest Oligocene but very likely ended after the formation of the Eocene erosional surface (e.g., Epis et al. 1980; Gregory and Chase 1994; Lindsey 1998). Rift-related extension is an ongoing process; therefore, the minimum age of extensional structures is no greater than maximum age of faulting and something less than the present.

Individual collection localities are from four principal areas within central and southern Colorado (fig. 3). First, the northernmost localities are associated with the Castle Creek structural zone (CCSZ) and the Elk Range thrust (ERT) (e.g., Bryant 1966). Isotopic age determinations from synkinematic intrusions indicate that the north-northwest-trending CCSZ was active by 72 Ma (Obradovich et al. 1969; Mutschler et al. 1988). This fault system consists of several steeply dipping, dextral-oblique, vertically anastomozing shear elements (Bryant 1966; Lamons 1991). The ERT has a more north-west-directed trend and may have up to 10 km of offset (Bryant 1966) related to northwest-directed compression (Wawrzyniec and Geissman 1995). In the waning stages of contraction, at ~35 Ma (Obradavich et al. 1968; Mutschler et al. 1988), the ERT was crosscut and intruded by the White Rock stock. Faulted localities within the stock generally consist of poorly organized fracture sets consistent within an overall extensional regime.

The second area, the Cripple Creek diatreme, is west of the Elkhorn thrust near Pikes Peak. The oldest volcanic unit of the diatreme is the Cripple Creek breecia, emplaced at about 30 Ma (Kelley et al. 1998), within an interpreted releasing bend geometry between two north-northwest-trending dextral-oblique shear zones.

The third area is near the so-called Villa Grove accommodation zone (Chapin and Cather 1994), the southern termination of the Arkansas graben to the north and the San Luis Basin to the south (e.g., Van Alstine 1974). The Monarch and Poncha Pass localities are within an east-west-trending band of diffuse deformation dominated by north-northwest- to south-southeast-directed extension (fig. 3).

The fourth area is broadly related to the frontal thrust of the Sangre de Cristo Mountains and extends from La Veta Pass to the western margin of Huerfano Park. Huerfano Park is one of the "Echo Park"–type Eocene basins that formed in the waning stages of the Laramide orogeny (Chapin and Cather 1983). Wawrzyniec (1996) suggested that these basins formed within a tensional bridge between the north-northwest-trending thrust to the west and the north-northwest-trending Isle fault further east. Similar to the Elk Range, the Huerfano Park Basin and the thrust that defines the western basin margin were locally affected by Oligocene intrusive activity (Penn and Lindsey 1996). West of La Veta Pass, parts of the Paleocene section were subsequently affected by younger, extensional

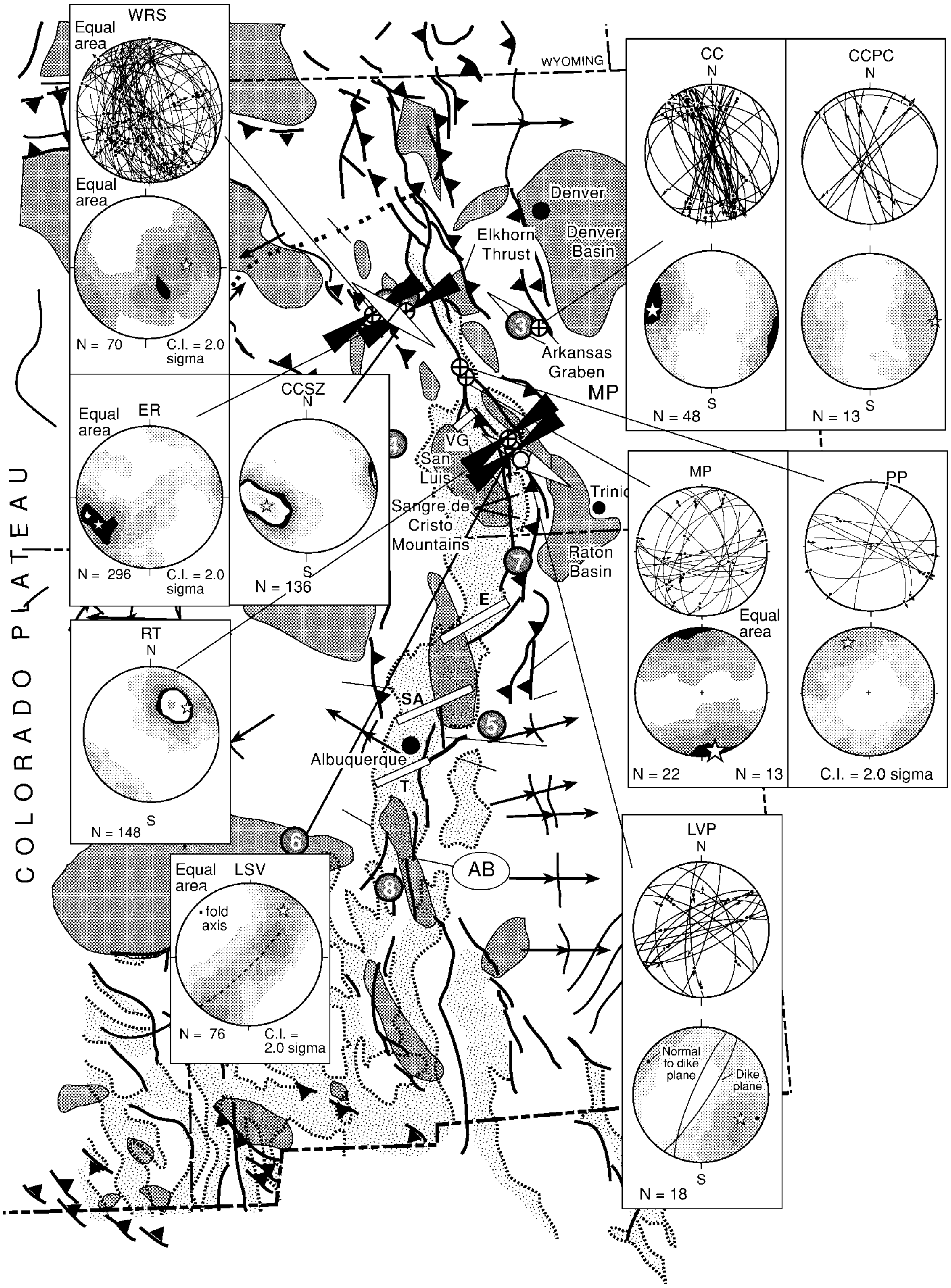

Figure 3. Generalized map and representative equal area projection contour plots of axes associated with Laramide uplift bounding structures and of s_1 associated with Oligocene extensional structures. A star indicates the mean orientation of the shortening and the extension direction, respectively. For equal area projections of actual fault data, the arrows indicate motion of hanging wall. Note that with exception to the White Rock stock data, all of the equal area projections contour plots on the left side of the figure are of s_3 axes, contour plots on the s_1 axes.

Table 1. Summary of Minor-Fault Strain Data

Location	Maximum age (Ma)	Number of samples	s_3	s_3
Elk Range thrust	72	296	**236/23**	131/25
Castle Creek structural zone	72	136	**245/33**	142/18
Sangre de Cristo frontal thrust, La Veta Pass (LSV)	K	76	**051/42**	293/25
Redwing thrust	K	148	**053/34**	317/10
White Rock stock	35	70	244/42	**086/45**
Monarch Pass	13	22	265/36	**168/10**
Poncha Pass	13	13	212/43	**334/29**
Poison Canyon Formation, east of La Veta Pass (LVP)	26	18	262/53	**121/31**
Cripple Creek diatreme	32	15	187/05	**279/13**
Faults in host rocks of the Cripple Creek diatreme	32	13	000/08	**090/02**

Note. Three individual locations near La Veta Pass include two kinematic sites (LSV, LVP) and one paleomagnetic site (LAV). Values in bold used in transcurrent model to estimate plate motion direction. K = Cretaceous.

faulting. Fault data were collected from thrust-related outcrops near Redwing (RT) and a roll-over anticline at La Veta Pass (LSV). West of La Veta Pass, northwest of Spanish Peaks, faults that cross-cut a series of north-northeast-trending dikes that intruded the uppermost Cretaceous to Paleocene Poison Canyon Formation were also measured (LVP). All fault plane measurements are in Wawrzyniec (1999); the mean kinematic directions are summarized in table 1 and figure 3. Inverted to a common hemisphere, the mean orientations of s_3 directions associated with Laramide-age structures have a shallow plunge and a trend that ranges from 051° to 065°. For rift deformation structures, the mean orientation of s_1 ranges from 269° to 348°. For all of these localities, contraction during Laramide-style deformation appears uniformly directed toward the east-northeast, whereas extension estimates during rift-related deformation are more dispersed.

Paleomagnetic Results

Many paleomagnetic studies have been conducted on Pennsylvanian through Triassic redbed strata east and northeast of the Colorado Plateau (table 2; fig. 2). We have augmented published paleomagnetic data with additional results from several localities in upper Pennsylvanian to lower Permian strata to assess magnitudes of vertical axis rotation of crust along the plateau's eastern margin (table 2). In our new results, progressive thermal demagnetization typically isolated a well-defined magnetization, unblocked above 600°C. In orthogonal demagnetization diagrams, these magnetizations trend to the origin and were readily evaluated using principal component analysis (fig. 4). Except for one site at the Indian Creek locality and three at La Veta Pass, all of these rocks yielded south-to-southeast declination and shallow positive or negative inclination magnetizations after structural correction, consistent with magnetization acquisition during the Late Paleozoic reversed-polarity superchron. The four anomalous sites yielded magnetizations of north-to-northwest declination and shallow inclination and are antipodal to most of the data. We assume that the hematite-dominated remanence was acquired early in the diagenetic history of each redbed sequence sampled and that it may not necessarily be a primary magnetization, as noted by Magnus and Opdyke (1991) for a Pennsylvanian redbed section along the Arkansas River. Reference of the data to the paleohorizontal, assuming penecontemporaneity or relatively early age of remanence acquisition, is unambiguous because there is no stratigraphic or structural evidence of substantial deformation of the strata during or soon after deposition. In fact, generally throughout the study area, stratigraphic sequences that include Pennsylvanian through mid-Cretaceous strata do not exhibit angular unconformities. All locality mean directions are exceptionally well defined, with α_{95} values ranging from 2.1° to 13.4°. Rotation estimates, in particular for Pennsylvanian to Permian strata, are associated with relatively high precision because each data set is of low dispersion, and the North American apparent polar wander path is well defined for this interval. With the exception of results from Carizzo Arroyo and Tejon, New Mexico, inferred clockwise rotations (tables 2, 3) are all <15°, but we note that all statistically significant declination discordancies are clockwise. Data from the Arkansas River, Red-

Table 2. Summary of Paleomagnetic Data

Study area	Lat./long. (°N/°W)	Age of strata/ remanence	n[a]	Corrected declination (°)	Corrected inclination (°)	α_{95} (°)	κ	R[b] (°)	ΔR[c] (°)	Data source
Rudi Reservoir (RR)	39.4/106.8	Pm.	26	158.5	−16.0	3.8	58	14.8	4.5	This study
Arkansas River (AR)	38.5/105.9	U. P.	38	136.2	−4.3	4.9	24	−1.9	5.0	Magnus and Opdyke 1991
Elk Range (ER)	…	P.-L. Pm.	5	145.9	−4.6	13.4	34	8.4	10.5	This study
Redstone (RS)	…	P.-L. Pm.	8	147.9	−10.5	8.3	45	10.7	6.8	This study
Castle Creek (CC)	…	P.-L. Pm.	7	143.0	.4	9.6	41	5.5	7.7	This study
La Veta Pass (LAV)	…	L. Pm.	17	152.7	−13.5	4.1	75	8.1	4.6	This study
Indian Creek (IC)	37.6/105.2	L. Pm.	17	168.7	−12.0	4.3	126	30.2	3.0	This study
Vail, Colorado (VL)	37.4/105.1	P.-Pm.	**145**	150.6	−1.1	3.2	19	12.9	3.9	Miller and Opdyke 1985
Las Vegas, N.Mex. (LV)	29.6/106.2	M. Tr.	8	152.3	−9.2	2.8	32	−14.6	8.8	Molina-Garza et al. 1996
Mora, N.Mex. (MR)	35.6/105.3	U. Tr.	8	359.1	7.9	10.0	55	−3.2	7.2	Molina-Garza et al. 1996
San Diego Canyon (SD)	36.0/105.3	L. Pm.	12	148.0	−1.4	7.6	89	2.6	3.7	Geissman and Mullally 1996
Tejon, N.Mex. (TJ)	35.7/106.7	U. Tr.	9	23.0	9.5	4.6	71	21.3	6.3	Molina-Garza et al. 1991
Tecolote Canyon (TC)	35.3/106.3	L. Pm.	15	168.7	3.3	6.1	3.8	24.6	5.2	Lundahl and Geissman 1999
Abo Pass (AB)	35.3/106.4	L. Pm.	**84**	152.0	−6.0	5.9	55	8.1	3.6	Steiner 1988
Carizzo Arroyo (CA)	34.4/106.4	L. Pm.	36	164.0	−2.6	2.1	32	20.3	4.7	This study

Note. U. = upper; M. = middle; L. = lower; P. = Pennsylvanian; Pm. = Permian; n = number of sites; α_{95} = 95% probability level confidence limit of directional mean; κ = precision parameter; R = rotation; ΔR = 95% probability level confidence limit of rotation estimate.

[a] Values in bold are number of samples from individual beds.

[b] Negative values represent counterclockwise rotations; positive values represent clockwise rotations.

[c] These values are a function of the quality of the reference apparent polar wander path for the time period in question. For Triassic data, the confidence limits may be too low because of a less clear understanding of the apparent polar wander path for North America. The following North American paleomagnetic poles were used for rotation estimates: 38°N/132°E (301 Ma); 43°N/127°E (281 Ma); 46°N/120°E (261 Ma); 44°N/108°E (240 Ma); 55°N/102°E (231 Ma); 58°N/88°E (221 Ma).

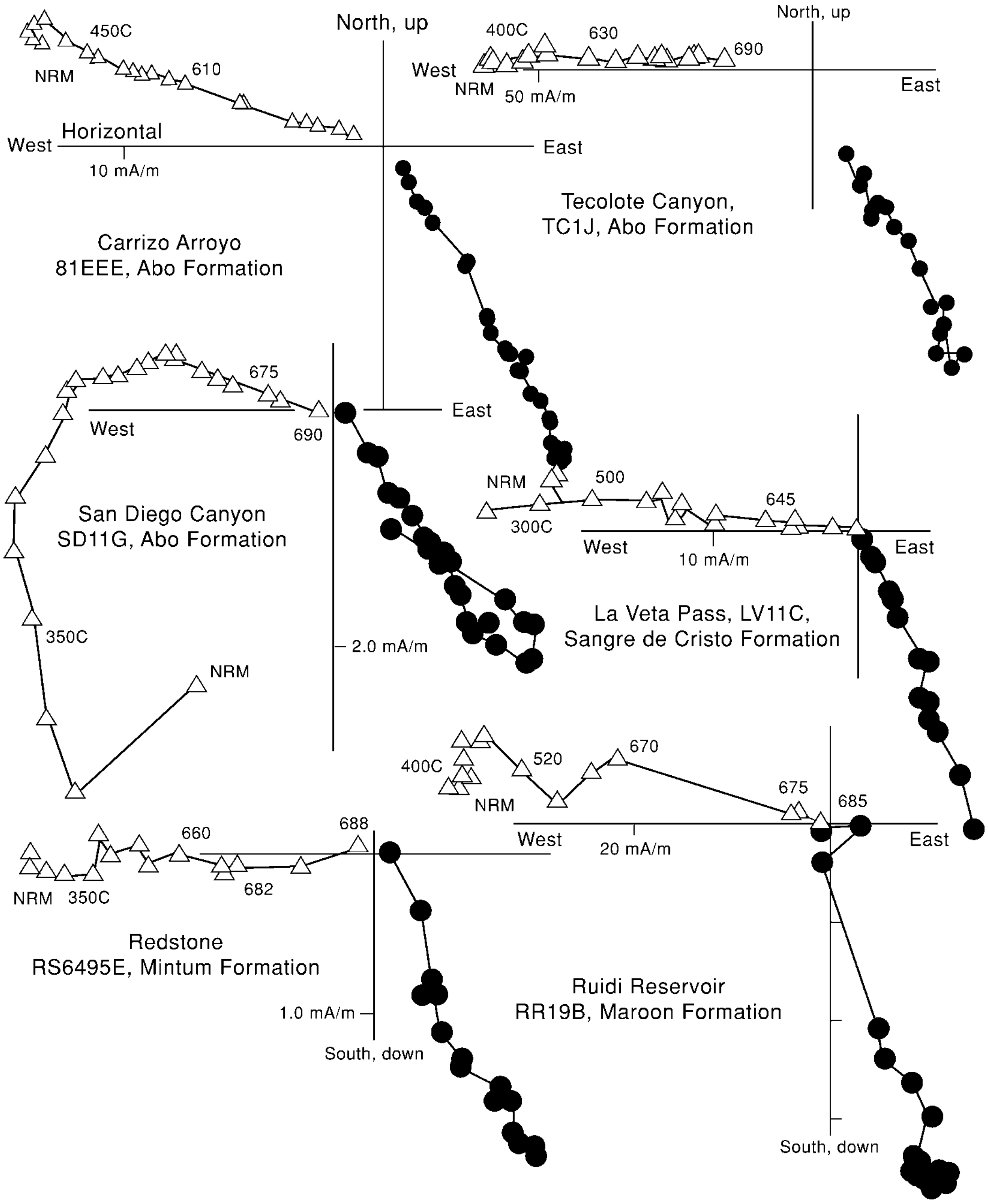

Figure 4. Representative orthogonal demagnetization diagrams from six localities showing typical response to thermal demagnetization of upper Pennsylvanian to lower Permian red beds considered in this study. In each, the endpoint of the magnetization vector is plotted in geographic coordinates onto the horizontal projection (*filled symbols*) and the true vertical projection (*open symbols*). Peak demagnetization temperatures (°C) are given beside the vertical projections. In each example, a magnetization of southeast declination and shallow inclination is isolated over a wide range of laboratory unblocking temperatures.

stone, Castle Creek, and Elk Range localities, all in Colorado, and the Mora locality, in New Mexico, show statistically insignificant rotation. Data from Rudi Reservoir, La Veta Pass, and Indian Creek localities indicate modest clockwise rotation. Overall, the data set reveals a progressive decrease in the magnitude of vertical axis rotation from south to north along the eastern margin of the Colorado

Table 3. Summary of Plate Motion Calculations

Location	Major trend (°)	Maximum age (Ma)	θ	α	PM directions[a]
Elk Range thrust (ER)	320[b]	72	84	78	062
Castle Creek structural zone (CCSZ)	350[b]	72	75	70	055
Sangre de Cristo frontal thrust, La Veta Pass (LAV)	320[b]	K[c]	89	88	052
Sangre de Cristo Frontal thrust, Redwing, Colo. (RT)	325[b]	K[c]	88	86	051
White Rock stock (WRS)	320[b]	35	54	18	*302*
Monarch Pass (MP)	290	13	58	26	*316*
Poncha Pass (PP)	270	13	64	38	*308*
Poison Canyon Formation, east of La Veta Pass (LVP)	…	26	…	…	*301*
Cripple Creek diatreme (CC)	340	32	61	32	*308*
Faults in host rocks of the Cripple Creek diatreme (CCPC)	340	32	70	50	*300*

[a] Directions reported in italics represent direction of divergence between the two plates. PM = plate motion.
[b] Measured to the nearest 5° (Tweto 1979).
[c] K = Cretaceous.

Plateau and the absence of significant vertical axis rotation along the northeast margin of the plateau (fig. 5).

Discussion

The kinematic data presented here are consistent with those of similar studies (e.g., Erslev 1993; Paylor and Yin 1993; Bird 1998; Johnston and Yin 2001) in that on the local scale, contraction associated with Laramide-style structures is relatively uniform (fig. 3), and on a regional scale, these results are consistent with east-northeast-directed transpression. Similar local-scale examples of convergence directions, often referred to as σ_1, are reported or implied along several structures throughout the central and southern Rocky Mountains (e.g., Evans 1993; Paylor and Yin 1993; Varga 1993; Molzer and Erslev 1995; Johnston and Yin 2001). Likewise, our findings agree well with many regional kinematic models for Laramide convergence (e.g., Hamilton 1988; Livaccari 1991; Erslev 1993). Rift-related structures, however, show increased dispersion in divergence orientation but are fully consistent with west-to-northwest-directed extension. The relative importance of northwest-directed extension is concordant with some previous studies of rift kinematics and extension (e.g., Woodward 1977; Lewis and Baldridge 1994). However, our findings, as well as theirs, do not support a hypothesis that the Rio Grande rift opened in association with a component of sinistral transtension. In a regional sense, the kinematics of sinistral extension requires southwest-directed extension along the north-south-trending Rio Grande rift; a point described by Chapin and Cather (1994) as a small rotation about a Euler pole located along the Uinta Arch. Although reasonable, this hypothesis fails to describe the observed variability associated with rift-related structures. Specifically, it does not address observations of dextral transtension along several rift-related structures in the southern (Lewis and Baldridge 1994), central (e.g., Woodward 1977), and northern (this study) parts of the Rio Grande rift. The conflict between sinistral and dextral transtension could indicate that (1) the structures analyzed represent different stages of rift kinematics, (2) evidence for northwest-directed extension is strictly a local phenomenon resulting from variation in fault geometry, and/or (3) the relationship between regional extension and kinematic data from minor-fault populations is poorly understood. Although the first two explanations remain plausible, we will attempt to better define the relationship between fault-kinematic data and regional kinematics related to both the Laramide orogeny and the younger Rio Grande rift. We propose that a dextral transcurrent hypothesis provides a less complicated and possibly more realistic explanation for Cenozoic deformation of the Cordilleran foreland. A key to this analysis is understanding the kinematics of block rotations that are well defined by a regionally extensive paleomagnetic data set from rocks within the eastern margin of the Colorado Plateau.

Paleomagnetic Data and Transcurrent Block Rotations. Most paleomagnetic data from uplifts within the margin of the Colorado Plateau reveal small and, for some localities, statistically significant clockwise rotation of crustal fragments. Most localities at the north-to-northeastern margin of the plateau reveal insignificant rotation. For example, rocks associated with the Sangre de Cristo thrust (fig. 2) were sampled at La Veta Pass and east Indian Creek lo-

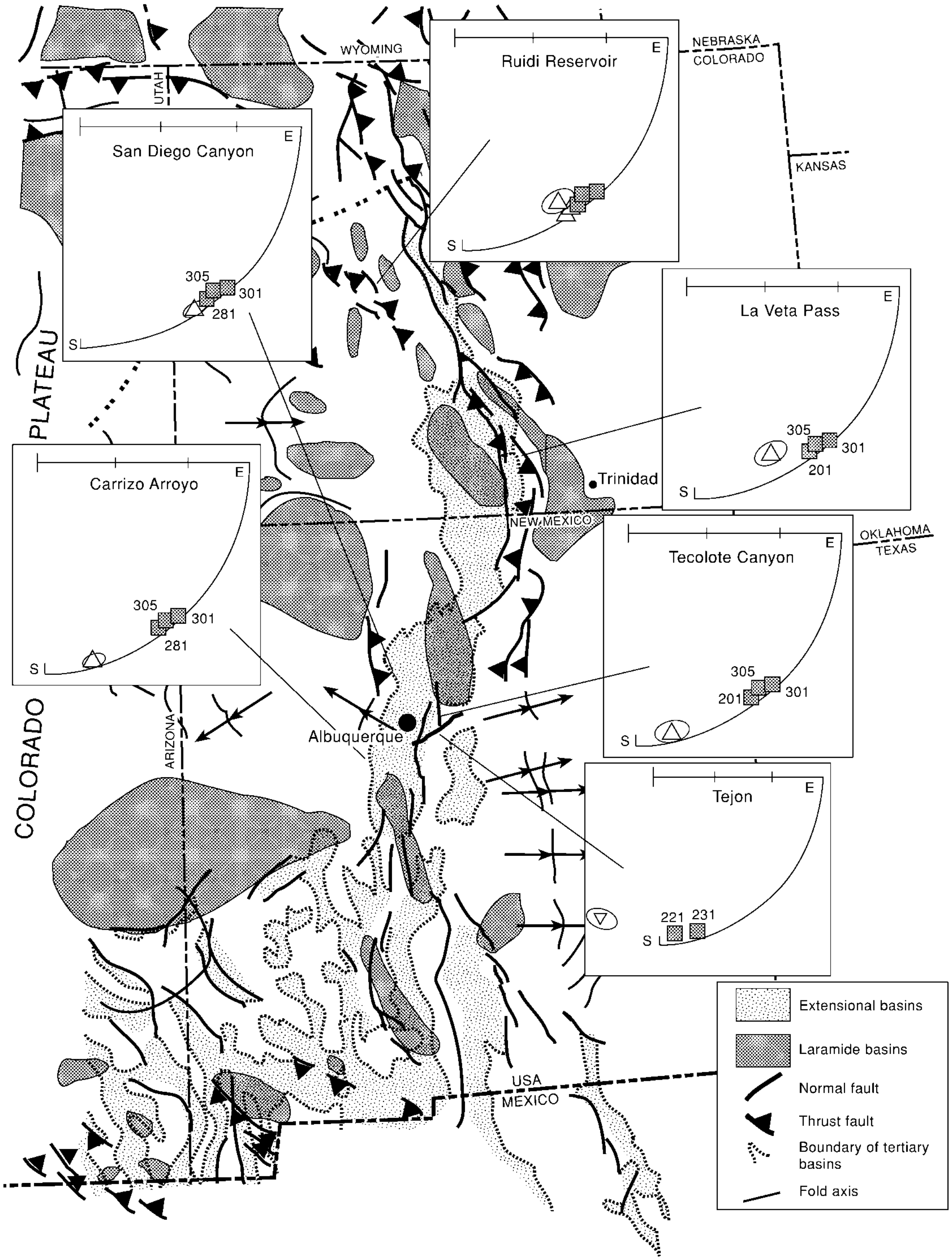

Figure 5. Generalized geologic map of the eastern and the northeastern margin of the Colorado Plateau. Inset diagrams show paleomagnetic data, plotted in the southeast quadrant of an equal area projection, with observed locality means (based on data from several individual sites; see table 3) and the associated reference directions with the inferred age of the reference directions given in millions of years.

calities, along the northern limb of an overall bow-shaped thrust where counterclockwise rotation would be predicted. Such rotation geometries have been observed associated with larger-scale, bow-shaped fold and thrust belts such as the Jura Arc (Hindle and Burkhard 1999) and the Cantabria-Asturias Arc of northern Spain (Weil et al. 2000). However, all sites in this part of the Sangre de Cristo Mountains, regardless of bedding orientation, consistently demonstrate clockwise rotations, which suggests that some larger-scale kinematic process is affecting these rocks. In a first-order sense, rotation of parts of Laramide-age uplifts may have occurred as a function of dextral transpressive shear of the eastern margin of the Colorado Plateau (fig. 6*a*). For moderate strains associated with dextral transpressive deformation, both the blocks and steeply dipping bounding structures must rotate in a clockwise sense as strain accumulates (Tikoff and Teyssier 1994; Teyssier and Tikoff 1998). The apparent kinematic consistency and clockwise rotation in association with Laramide structures suggests that strains are both moderate and consistent with dextral transpression.

The paleomagnetic data from upper Paleozoic to lower Mesozoic redbeds along both margins of the Rio Grande rift contrast with those reported from Tertiary-age rocks within parts of the rift. Brown and Golombek (1985, 1986) and Salyards et al. (1994) obtained data from Tertiary volcanic and shallow intrusive rocks and upper Tertiary detrital strata from parts of the Española Basin that suggest that parts of the basin experienced counterclockwise, rather than clockwise, rotation. Such counterclockwise rotation is consistent with a model of dextral transtension affecting the eastern margin of the Colorado Plateau since the mid-Tertiary (fig. 6*b*). However, we must underscore some concerns about the overall reliability of this data. The detailed work of Salyards et al. (1994) involved mid-Miocene strata of the Tesuque Formation. At each locality, mean directions of magnetization were estimated on the basis of sample data and did not include an analysis of site, or bedding mean, directions. The within-locality scatter of results was high, but with high numbers of samples, the confidence limits are artificially reduced. In this context, the apparent declination discrepancies provide rotation estimates that vary from 0° (and statistically insignificant) to $-28.5° \pm 10.6°$. Brown and Golombeck (1985, 1986) reported a broader range of rotation estimates for Tertiary igneous rocks, from $+19.5° \pm 9.1°$ to $-90° \pm 11.1°$. Although paleomagnetic data from volcanic and shallow intrusive rocks typically provide far better determina-

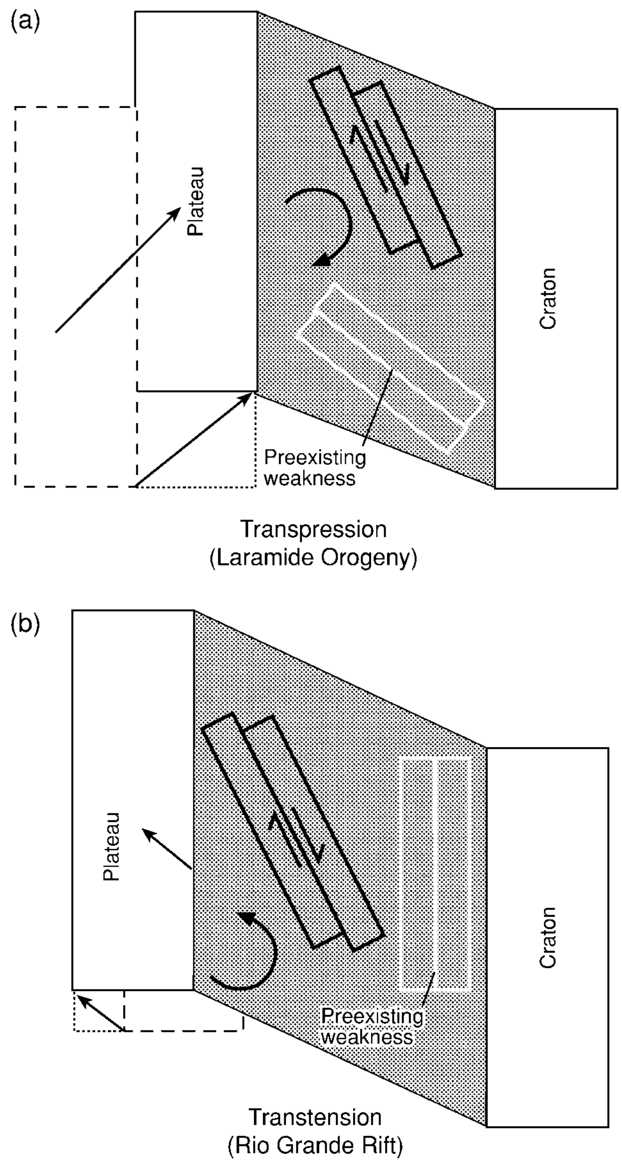

Figure 6. Map-view diagrams showing how individual blocks may rotate during transcurrent deformation. Dashed lines show predeformation position of shear zone elements. *a*, During transpression, clockwise vertical axis rotation and concomitant dextral simple shear accommodates narrowing of the deforming zone. *b*, During transtension, anticlockwise vertical axis rotation and concomitant dextral shear accommodates broadening of the deforming zone.

tions of an instantaneous geomagnetic field, the sampling record may be very sporadic and short lived. Sufficient averaging of the geomagnetic field to estimate rotations with respect to an expected time-averaged reference direction requires a large number of independent readings of the field over several millions of years. At several localities, it is doubtful that the data reported by Brown and Golombek (1985, 1986) satisfy these criteria.

We will nonetheless assume that the paleomagnetic data from the Española Basin, central Rio Grande rift, indicate that at least parts of the basin experienced counterclockwise rotations. This is consistent with the hypothesis of Muehlberger (1979) that the Española Basin, bounded by the Embudo fault zone (northwest boundary), the Pajarito–La Bajada–San Francisco–Sandia fault systems (western boundary), the Tijeras-Canoncito fault zone (southeast boundary), and the Pecos-Picuris fault (eastern boundary/rift fault), experienced young rigid block counterclockwise rotation. Again, in contrast to models involving left-lateral transtension, we argue that such counterclockwise rotation of blocks within the rift can be explained by dextral transtension (fig. 6*b*). The rotation of rift blocks and related bounding structures could have occurred if vertical axis rotations accommodate part of the overall east-west-directed extension of the deforming eastern margin of the Colorado Plateau. Furthermore, modest counterclockwise rotation of parts of the Española Basin is consistent with a model of mid-Tertiary dextral transtension along the plateau's eastern margin. Assuming a west-to-northwest-oriented least principal stress direction, and therefore a similar direction for maximum elongation, left slip along the northeast-trending Embudo and Tijeras-Canoncito fault zones during some part of their mid-Tertiary and younger history (Muehlberger 1979) could be explained as an authentic component to overall right slip along the north-trending western and eastern margins of this part of the Rio Grande rift, which could result in localized counterclockwise rotations. To further test this hypothesis of Cenozoic dextral transcurrent deformation, it is necessary to see how these rotations relate to both timing of deformation and the observed pattern of strain in the context of relative plate motions.

Timing of Deformation. The approximate age of Laramide structures is well established (fig. 7) either by the age of the sedimentary rocks affected by structures measured in this study or by isotopic age determinations of synkinematic intrusions. The maximum age of faulting in the Castle Creek structural zone is indicated by several ~72 Ma intrusions that affected and were affected by oblique-dextral deformation (Tweto 1977; Lamons 1991; Wawrzyniec and Geissman 1995). The timing of deformation along the Sangre de Cristo Mountains is well defined by the age of strata in the Raton and Huerfano Park Basins east of the main frontal thrust. Sediments from the uplift are no older than 65–72 Ma (Dickinson et al. 1988; Lindsey 1998). Fold axes within Eocene strata of the Huerfano Park Basin parallel the trend of the frontal thrust, suggesting that northeast-directed convergence, as indicated by the minor-fault data, is concurrent with folding of basin sediments.

Two areas we selected to address the earliest phase of Rio Grande extension were affected by Ol-

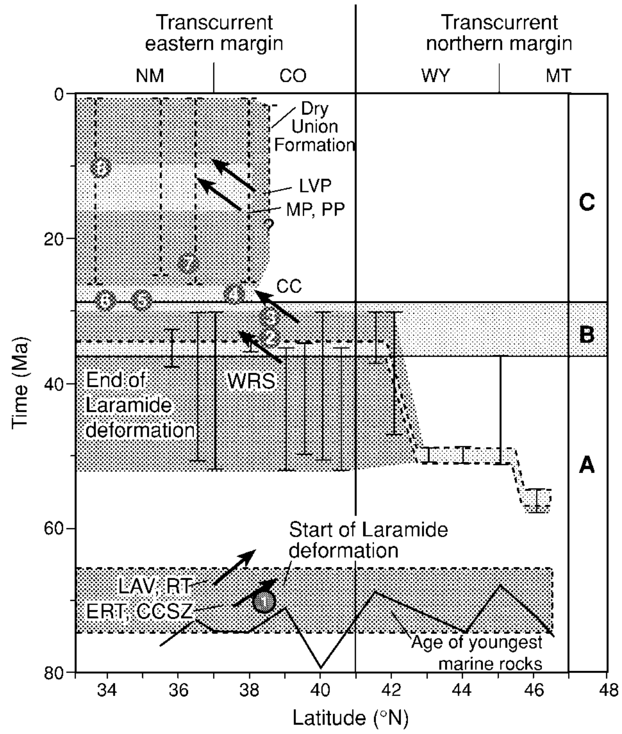

Figure 7. Time versus latitude chart schematically representing the timing of the Laramide orogeny and Rio Grande rifting (modified from Dickinson et al. 1988; Chapin and Cather 1994). Numbered locations refer to igneous events in figure 2. Solid error bars show the range of cessation of sedimentation in transpressional basins. Dashed error bars show the age range of sedimentation of the Santa Fe Formation within basins of the Rio Grande rift. Dashed polygons show the beginning and end of the Laramide as presented in Dickinson et al. (1988). *A*, Laramide orogeny and continued northeast-directed convergence. *B*, Transition phase lasting 1–6 m.yr., in which extension is likely given the widespread occurrence of volcanic activity. *C*, Rio Grande rift marked by the onset of sediment accumulation (Santa Fe Formation); rifting may continue to the present. The rift may terminate near the Arkansas graben (Dry Union Formation) because the trend of bounding structures changes to the northwest and becomes subparallel to the calculated divergence direction.

igocene magmatism. The White Rock stock and Cripple Creek diatreme are thought to have been emplaced after Laramide deformation and before or during the earliest stages of rifting. Although this interpretation may be true for the Cripple Creek diatreme, some uncertainty remains regarding the timing of contraction and emplacement of the White Rock stock. Recalibrated K-Ar age estimates from the stock yielded dates of ~35 Ma (Obradovich et al. 1969; Mutschler et al. 1988), and crosscutting relations suggest that the stock stitches the Elk Range thrust (i.e., the pluton was emplaced along the thrust and in places cuts the thrust). However, outcrop exposures of fault gouge from the thrust plane reportedly contain fragments of granodiorite similar to the White Rock stock, suggesting that faulting may have continued after emplacement (Allen 1968). Faults yielding kinematic data from the White Rock stock, which indicates localized transtension, may have formed after or near the end of northeast-directed convergence. Data from the bounding structures of the Cripple Creek diatreme (table 1) that are thought to accommodate multiple phases of strain, including Early Eocene to possibly Oligocene dextral slip, are consistent with dextral shear along these structures. The associated extension direction is similar to that defined by faults that clearly cut igneous rocks of the diatreme itself. The Cripple Creek diatreme was emplaced between 32 and 27 Ma (Kelley et al. 1998). Surface and subsurface field relations suggest that the diatreme was emplaced into an incipient basin (Lindgren and Ransome 1906), possibly associated with a structural dome of Laramide affinity at the intersection of north-northwest-trending dextral and northeast-trending sinistral strike-slip structures (Birmingham 1987). Also, data from faults restricted to the diatreme's oldest rocks reveal a poorly documented phase of north-south-directed thrusting, suggesting that north-south shortening was only important during the earliest phase of diatreme evolution. We suggest this phase may represent a youngest stage of compressional tectonics within the Cordilleran foreland. We interpret these observations to be consistent with dextral transtension during diatreme emplacement.

The only structures we examined that are directly associated with Neogene extension are adjacent to the Villa Grove transfer zone, between the San Luis rift basin and the Arkansas graben. Here, crystalline rocks of the northernmost Sangre de Cristo Range are separated from crystalline rocks of the southernmost Sawatch Range by a few kilometers of Tertiary gravels of the Dry Union Formation. On the basis of exposures of ash beds within the Dry Union Formation, Van Alstine (1974) interpreted these gravels to be Late Miocene or younger; therefore, the structures are exclusively Neogene in age.

The timing relations provide a clear basis for separating Laramide contractional from younger, extensional structures. In the absence of rigorous estimates of the minimum age of faulting, a limitation in any study of fault kinematic data, it is impossible to accurately determine the time between contraction and extension. Based on the observed crosscutting relationships, however, the gap may be short lived (<10 m.yr.). As revealed by minor-fault populations, the kinematics of these structures are established by the maximum age of faulting. Given the oblique-slip geometries of most of the minor faults and major structures, we contend that the kinematic and paleomagnetic data can be interpreted in the context of regional-scale, dextral-transcurrent deformation. These data provide insight into relative plate motions between the plateau and the craton.

Transcurrent Deformation and Plate Motions. As a first-order approximation, we assume that the eastern margin of the Colorado Plateau has experienced no slip partitioning since the onset of Laramide deformation. This assumption implies that bulk deformation along the eastern margin was not separated into purely dip-slip (thrust or normal faults) and purely strike-slip structures. The absence of such structures and the overwhelming volume of field data revealing oblique-slip faults support this assumption. In a non-slip-partitioned system, the relationship between convergence and s_3 and divergence and s_1, respectively, is described by the following relation (Teyssier et al. 1995):

$$\theta = \left(\frac{\alpha}{2}\right) + 45°,$$

where θ is the angle between the kinematic directions (s_3 or s_1) and the trend of the major structure associated with the population of minor faults. The term α is the angle between the trend of the major structure and the plate motion direction. Values of θ and α range from 45° to 90° and 0° to 90°, respectively. Pure strike-slip deformation is characterized by $\alpha = 0°$; therefore, $\theta = 45°$. Pure dip-slip faulting is characterized by $\alpha = 90°$; thus, $\theta = 90°$. These conditions also apply to the trend of the plate boundary (fig. 8). For each of the individual structures we examined within the plate boundary, we obtained a value of θ for each by determining the acute angle between the orientation of s_3 and the

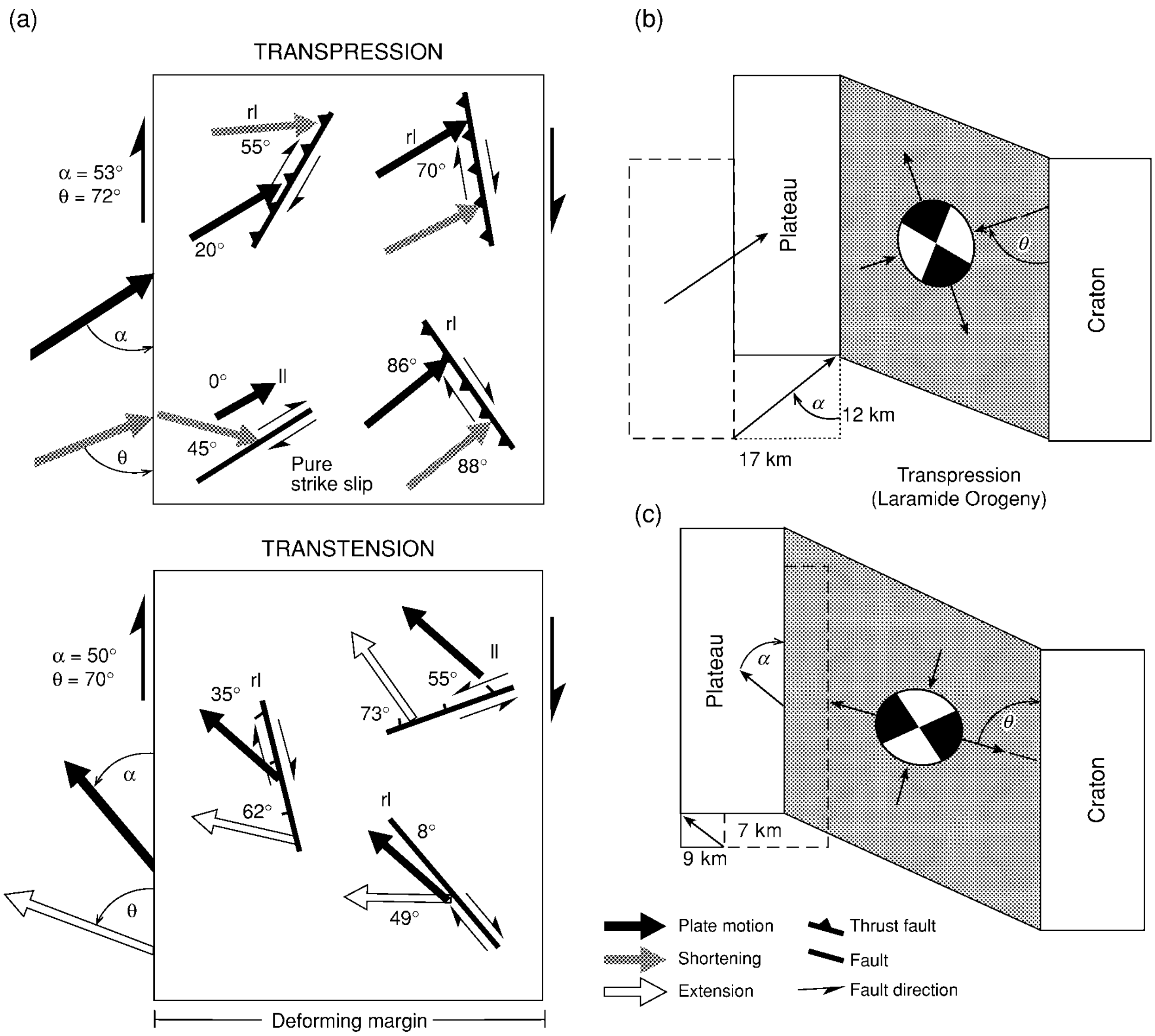

Figure 8. *a*, Map-view diagram showing the relations between shear zone trends, plate motion direction, and kinematic directions (s_1 and s_3). *b*, Map-view diagram representing the deforming eastern margin of the Colorado Plateau (*gray*) located between a fixed craton and an obliquely converging plateau (Laramide orogeny). *c*, Same as above, except for obliquely diverging plates (Rio Grande rift). Also depicted are the geometric relations used to derive northward translation estimates for both tectonic events.

trend of the related major contractional structure associated with the minor-fault population. For extensional structures, we measured the acute angle between s_1 and the trend of the related major structure. Using the above relation, we calculated motion directions for each major structure. In the context of north-directed plateau motion, this analysis (figs. 3, 7; app. A1 in Wawrzyniec 1999) yields consistent plate motion directions for each locality. The consistency further validates the assumption of no (or at least minimal) slip partitioning. If partitioning was important, and we had failed to account for it, each structure of different orientation would yield a distinct plate motion (see Teyssier et al. 1995).

The inferred absence of slip partitioning is also supported by geologic observations. First, in the area studied, there are no documented unequivocally syn- or post-Laramide steep-dipping, dextral strike-slip faults with large offsets (>1–3 km). Also, no structures share a common trend, with one being pure strike slip and one being pure dip slip.

Tweto and Sims (1963) and Tweto (1977) argued that most of the faults in central Colorado follow preexisting weaknesses of Precambrian ancestry. Structures can be reactivated under conditions where stress is not predictably oriented for brittle failure and fault movements are commonly oblique, with convergence or divergence and translation occurring simultaneously (e.g., Teyssier and Tikoff 1998). Thus, partitioning of slip into purely strike-slip and purely dip-slip faults is an unreasonably complicated model to explain observed regional kinematics. Finally, our paleomagnetic results, all from tilted strata, indicate a regional pattern of modest clockwise rotation of fault-bounded blocks along the eastern margin of the plateau. Although the inferred rotations can be produced by many mechanisms, they are consistent with non-slip-partitioned, dextral-transcurrent deformation. In light of all of these observations, we assert that the absence of pure strike-slip fault systems with discernible Cenozoic offset, in concert with paleomagnetic data and the likelihood of fault reactivation, affirms the validity of the assumption of lack of slip partitioning.

Plate motion results in combination with estimates of east-west contraction and subsequent extension along the eastern margin of the plateau allow us to estimate the magnitude of northward translation since inception of Laramide deformation. Chase et al. (1992) estimated about 27 km of east-west shortening at the latitude of Denver based on minimum values of shortening for the Front Range–Rampart fault (11 km), the Elkhorn-Williams thrust (6 km), and the Elk Range thrust (10 km). The estimate for the Elk Range thrust, however, is based on a model proposed by Bryant (1966), in which thrusting is associated with a gravity slide of Paleozoic rocks off the Sawatch uplift. The magnitude of offset is estimated from a "possible window" west of the Castle Creek structural zone south of Aspen. If these interpretations are correct, then deformation along the Elk Range thrust is related to exhumation, and the estimate of shortening has no bearing on the amount of east-west contraction across the eastern margin of the plateau. Alternatively, if the gravitational-slide hypothesis is incorrect, then the amount of shortening along the Elk Range thrust must be reevaluated in the context of contractional structures to explain the field observations. Based on recent findings (Lamons 1991; Wawrzyniec and Geissman 1995) and this work, the new estimate of east-west shortening must take into account the oblique nature of shortening across the Elk Range thrust. Assuming a conservative estimate of about 17 km of east-west contraction, a mean plate convergence direction of 054° yields an estimate of minimum northward translation of the plateau during Laramide contraction of about 12 km (fig. 8*b*). If the 10-km shortening estimate along the Elk Range thrust is valid, then a minimum northward translation estimate may be as high as 19 km.

A similar estimate can be made for mid-Cenozoic and younger rift-related motion of the plateau. Based on seismic data, cross sections across the San Luis Basin indicate 8%–12% (~9 km) extension (Kluth and Schaftenaar 1994). Using this value as representative of extension across the northern Rio Grande rift and a mean divergence direction of 312°, we estimate about 8 km of northward translation during rifting (fig. 8*c*). In total, we estimate a minimum of about 20–27 km of northward translation of the plateau since the onset of the Laramide orogeny.

There is a remarkable consistency in the calculated plate motions of the Colorado Plateau relative to the craton (figs. 3, 7; table 1). There is also reasonable agreement between our translation estimates and conservative estimates of syn- and post-Laramide northward translation of the plateau (20–35 km; Woodward et al. 1997; Woodward 2000) that are based on stratigraphic piercing lines. Cather (1999), however, proposed a minimum of 85 km of northward translation on the basis of an alternative interpretation of the same stratigraphic relationships. We recognize that some stratigraphic relations and apparent piercing lines across the eastern margin of the plateau permit such large offsets. Existing data, however, on the distribution of stratigraphic pinch outs and isopachs limit total dextral offset across the margin to be between about 25 and 135 km since the latest Cretaceous (Cather 1999; Ingersoll 2000; Lucas et al. 2000; Woodward 2000). On the basis of our estimates of crustal shortening north and northeast of the Colorado Plateau since the mid-Cretaceous, we argue that the larger-magnitude estimates of dextral offset and northward translation of the plateau, inferred by Cather (1999), Karlstrom and Daniel (1993), and Cather and Karlstrom (2000), are excessive and not well reflected in the observed structures with offsets of appropriate age. Moreover, the large-magnitude estimates of northward translation are best supported by apparent offsets of pre-Laramide strata or features within Precambrian basement rocks (e.g., Woodward et al. 1997), an observation that further undermines the credibility of offset estimates based on field relations involving rocks ostensibly younger than mid-Cretaceous in age.

Tectonic Implications

Laramide features in the southern Rocky Mountains are characterized by long, wide, asymmetric uplifts flanked by deep basins with locally derived detritus (Dickinson and Snyder 1978). Uplifts and basins trend north-south along the eastern margin of the Colorado Plateau (Chapin and Cather 1983; Dickinson et al. 1988). Structures associated with these features have been interpreted to be the result of northeast-directed convergence (e.g., Woodward et al. 1997; Bird 1998), as supported by the kinematic data reported here. Our results for Neogene rift-related structures, however, in part challenge previous interpretations of the nature of deformation along the rift.

The part of the Rio Grande rift defining the eastern margin of the Colorado Plateau extends from central New Mexico to central Colorado and is characterized by an array of north-northeast-trending, en echelon, right-stepping, asymmetric basins. These overprint several uplifts and basins that were actively defined during the earlier Laramide orogeny (fig. 2). The en echelon pattern of basin formation, and other field relations, were interpreted to indicate a component of sinistral slip associated with early, mainly Miocene, southwest-directed extension and opening of rift basins (e.g., Kelley 1982). Sinistral slip parallel or subparallel to the axis of the Rio Grande rift would necessarily result in a south-directed component of translation of the plateau relative to the craton. The most rapid period of extension (Middle to Late Miocene) is thought to coincide with about 1.5° of clockwise rotation of the plateau about a Euler pole centered on the Uinta Arch (Chapin and Cather 1994). Our results, in contrast, are consistent with a dominant component of east-west to northwest-southeast extension and a lesser component of dextral displacement along north-south-trending basin-bounding faults.

Evidence of sinistral shear, as summarized by Kelley (1982), includes right-stepping en echelon rift basins, sinistral drag folds along north-south-trending structures, sinistral structures that trend 060°, and sinistral offset of pre-Cenozoic stratigraphic pinch outs across rift basins. We find the sum of evidence less than conclusive. First, right-stepping, en echelon patterns of faulting and basin formation are potentially characteristic of dextral shear (e.g., Aydin and Nur 1982). In fact, Karlstrom et al. (1999, p. 158) argued that "the basic right-stepping configuration of the Rio Grande rift mimics a Laramide right-stepping oblique slip deformation system." They also described this deformation system as dextral transpressional, an idea first implied by Chapin and Cather (1981, 1983). An implicit possibility to this hypothesis is that this pattern of right-stepping Laramide-age uplifts is associated with transtensional basins localized as flexural basins between uplifts (Kellogg 1996) or by the formation of tensional bridges between north-northwest-trending dextral reverse faults (Wawrzyniec 1996). Such basins do exist and have been described as "Echo Park"–type basins by Chapin and Cather (1981) and as intermountain basins by Dickinson et al. (1988). The hypothesis also implies that reactivation of the right-stepping geometry would uplift older basins during sinistral transtension or act to deepen the older, Laramide basins during dextral transtension. Given that several Laramide-age basins appear to be preserved beneath some basins of the right-stepping Rio Grande rift (e.g., Galiesteo-El Rito Basin and Huerfano Park, San Luis "Echo Park"–type basins; fig. 2; Chapin and Cather 1981), the observed geometry of Laramide and rift-related basins is most consistent with dextral transtension. Second, drag folds are notoriously unreliable as an indicator of absolute offset. Surface exposure of folds can easily yield an apparent sense of motion. Perhaps, more importantly, their interpretation requires a thorough understanding of the fold geometry and the timing of fold development with respect to fault slip; folds can form any time before faulting and may be the product of an entirely unrelated tectonic regime. Unfortunately, the simple descriptions provided by Kelley (1982) fall short of providing a clear picture of fold timing and geometry and therefore do not provide any conclusive insight. Third, long-lived, sinistral-oblique faults that trend 060° (e.g., the Tejeras Canyon fault near Albuquerque; Karlstrom et al. 1999) are compatible with dextral shear along the eastern margin of the plateau. For the Laramide orogeny, the orientations of such structures are sinistrally oblique to the resolved plate convergence direction of 054°. During Neogene rifting, this same structure could also accommodate sinistral shear as a secondary component to overall northwest-directed extension. In other words, sinistral shear along the Tejeras Canyon fault, and other faults of similar orientation, are compatible with both dextral transpression and dextral transtension along the north-south-trending eastern margin of the Colorado Plateau. Finally, the validity of using pre-Cenozoic stratigraphic piercing points to demonstrate sinistral shear in the Neogene is debatable. However, where rift sediments do not obscure these features, the stratigraphic piercing points consistently demonstrate, regardless of the magnitude of translation, bulk dextral shear associated with post–mid-Cretaceous northward translation of the plateau (Woodward et al. 1997; Cather 1999). Thus, the stratigraphic piercing points appear inappropriate for testing a sinistral transtensional hypothesis for rift kinematics as proposed by Kelley (1982) and implied by Chapin and Cather (1994). We contend that the evidence supporting translation during major phases of rifting is consistent with dextral transtension, as also discussed by Lewis and Baldridge (1994), which resulted in the continued northward movement of the plateau during the majority of time spanning Rio Grande rift formation.

In a more regional context, northward plateau translation and attending dextral shear, from the latest Cretaceous to today, require a driving mechanism. A preferred hypothesis for Laramide deformation is the northeast-directed subduction of a subhorizontal lithosphere slab (Dickinson and Snyder 1978), with late Laramide, northeast-directed convergence driven by extensional collapse southwest of the plateau. Although the latter mechanism was undoubtedly important as plate convergence rates waned through the Eocene, our results are consistent with prolonged dextral, oblique plate interaction that ultimately changed to west-to-northwest-directed extension within much of the Cordillera in the Neogene and, in some areas specifically, by the Early Oligocene. Field relations along the eastern margin of the Colorado Plateau reveal the potential role of continuous, dextral plate interactions along the western continental margin since the Late Cretaceous in dictating structural relations observed far inboard of the margin of the North American continent.

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