Implications of Jurassic, Cretaceous, and Proterozoic piercing lines for Laramide oblique-slip faulting in New Mexico and rotation of the Colorado Plateau

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ABSTRACT

Regional isopach patterns and pinch-out data for nine stratigraphic units of Jurassic and Cretaceous age are either permissive or supportive of significant dextral slip of Laramide age along the eastern Colorado Plateau boundary in New Mexico. The best-constrained dextral offset estimates are for the Sand Hill–Nacimiento fault system (20–33 km) and the previously published 13 km estimate for the Defiance monocline, which together yield a cumulative offset of 33–46 km. Mesozoic stratigraphic constraints for other Laramide fault systems are less precise, and typically provide only maximum limits for possible dextral offsets because of widely spaced control points and broad areas of Tertiary erosion. These less precise constraints allow as much as 40–60 km of Laramide dextral slip along what is now the Rio Grande rift and as much as 110 km across the entire breadth of the Laramide deformed zone in central and northern New Mexico.

Well-documented dextral offsets of Proterozoic lithologies and structures across the Tusas-Picuris fault system (15 km) and Picuris-Pecos fault (37 km) probably represent minimum Laramide displacements because of the need to account for sinistral components related to other deformations. These displacements, when combined with dextral offsets along Sand Hill–Nacimiento and Defiance structures, yield a minimum dextral offset of ~85 km for Laramide structures in northern New Mexico. This minimum dextral offset is approximately equivalent to the amount of Laramide crustal shortening on and northward of the Colorado Plateau, a result that argues against nearby Euler pole locations for Laramide rotation of the Colorado Plateau relative to cratonic North America. Geological constraints allow ~0° to 3° of Laramide clockwise rotation of the Colorado Plateau. Additional clockwise plateau rotation during late Cenozoic development of the Rio Grande rift was 1° to 1.5°. Geological constraints thus indicate that clockwise rotation of the Colorado Plateau from combined Laramide and Rio Grande rift deformations was between about 1° and 4.5°.

INTRODUCTION AND TECTONIC OVERVIEW

The Laramide orogeny (ca. 80–40 Ma) has been relatively little studied in New Mexico as compared to other areas in the Rocky Mountains, principally because of the difficulty in seeing through the effects of subsequent Rio Grande rifting. Analysis of Laramide deformation beneath rift basins has been restricted largely to identification of areas of relative Laramide uplift versus subsidence based on subsurface stratigraphic data or paleocurrent and provenance analysis of Laramide synorgenic deposits exposed along rift flanks (Cather, 1983, 1992; Sales, 1983; Brister and Gries, 1994). Unrecognized Laramide faults may have been buried beneath basins of the Rio Grande rift because Laramide faults were commonly reactivated during late Tertiary extension.

Major Laramide faults are widely distributed in central and northern New Mexico. Most strike north to northeast (Fig. 1). Studies during the past 40 yr in New Mexico have demonstrated dextral components of slip on many Laramide faults (Fig. 1; Table 1). Because the relative amounts of strike slip versus dip slip are unknown on many of these faults, I refer to them collectively as dextral-oblique, although I recognize that some of these faults eventually may prove to be closer to either the strike-slip or dip-slip end members. Faults that display dextral slip indicators (Table 1) generally strike north to northeast, dip moderately to steeply, and typically display evidence for reverse components of slip. Normal components of Laramide slip, however, have been documented on dextral-oblique faults near Albuquerque (Rio Puerco fault system, Slack and Campbell, 1976; parts of Tijeras-Cañoncito fault system, Stearns, 1953a; Abbott, 1995), faults that may be related to a releasing bend in the regional dextral-oblique fault system in the southern Rocky Mountains (Cather, 1992).

At the latitude of Santa Fe, dextral-oblique Laramide faults occupy a zone at least 320 km wide bounded on the west by the Defiance monocline (Kelley, 1955, 1967) and on the east by the frontal faults of the Sangre de Cristo uplift (O'Neill, 1990). Dextral-reverse faulting along the East Kaibab monocline (Davis and Tindall, 1996) indicates that significant Laramide dextral components of fault displacement were locally important as far west as the Grand Canyon area of the Colorado Plateau. Within the dextral-oblique zone of central and northern New Mexico, the principal locus of Laramide deformation was in the east-central part, as shown by the distribution of small en echelon basins of late Laramide age (Fig. 1; Echo Park–type basins of Chapin and Cather, 1981, 1983). Laramide faults within this central zone exhibit relatively large throws as well as evidence of dextral slip (Table 1). For these reasons, faults of the central zone (Picuris-Pecos fault and its southern bifurcations, Sand Hill–Nacimiento fault system, and Laramide faults now buried beneath basins of the Rio Grande rift) probably accommodated the majority of Laramide dextral slip in New Mexico. At the latitude of Santa Fe the central zone has the cross-sectional form of an enormous positive flower structure (Cather, 1992, Fig. 10). Laramide dextral displacements decrease northward into Colorado due to increased components of shortening in that area (Chapin and Cather, 1981, p. 192).

Evidence for dextral components of slip along major Laramide faults in central and northern New Mexico is, in most cases, of two types (Table 1): (1) kinematic data based on slicken-

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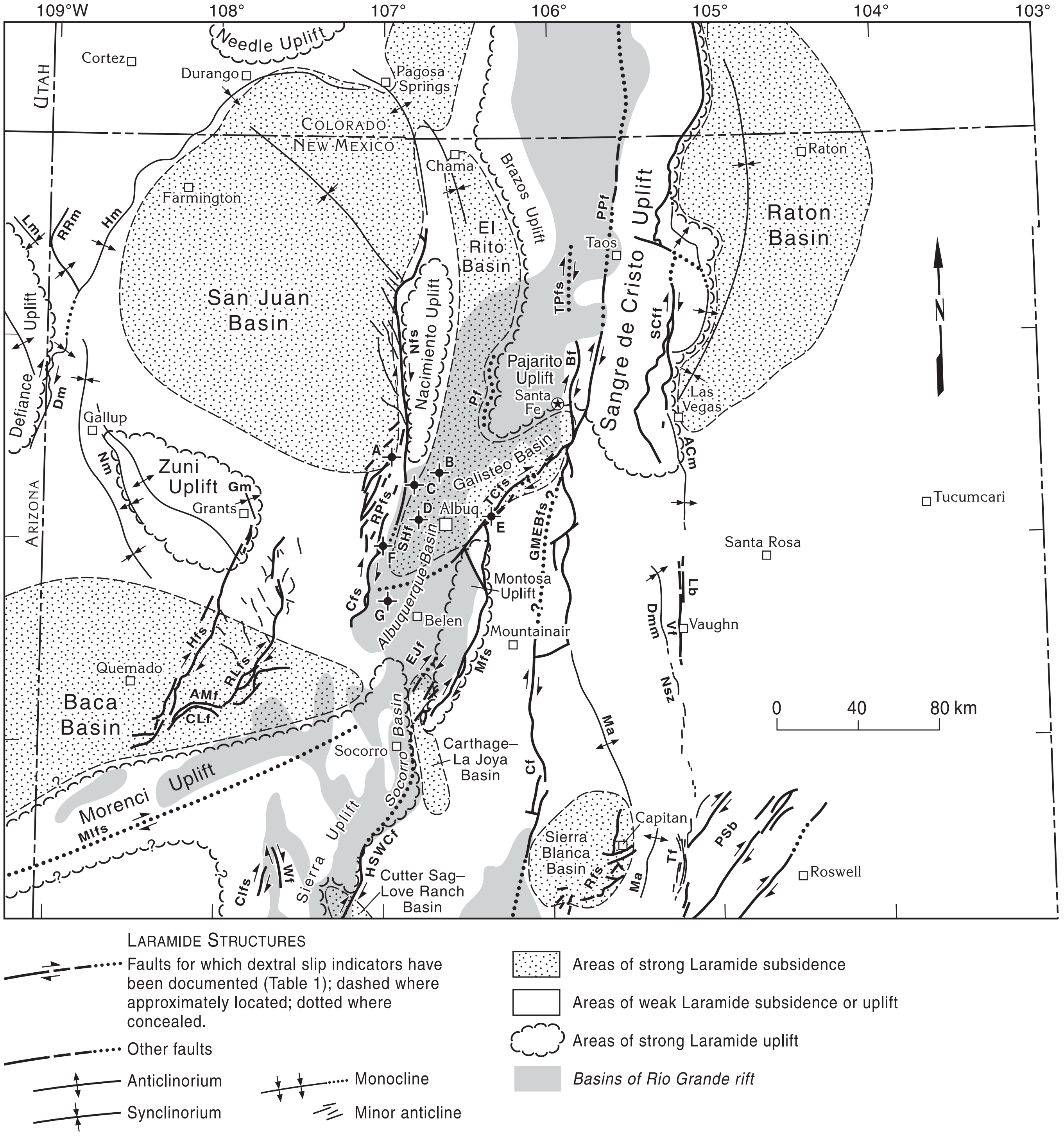

Figure 1. Map showing Laramide uplifts, basins, and structures, Rio Grande rift basins, and selected wells near Albuquerque. Abbreviations of names of Laramide structures are: AMf—Alegres Mountain fault; ACm—Anton Chico monocline; Bf—Borrego fault; Clfs—Chloride fault system; Cf—Chupadera fault; Cfs—Comanche fault system; CLf—Cox Lake fault; Dm—Defiance monocline; Dmm—Derramadera monocline; EJf—East Joyita fault; GMEBfs—Glorieta Mesa–Estancia basin fault system; Gm—Grants monocline; Hfs—Hickman fault system; Hm—Hogback monocline; HSWCf—Hot Springs–Walnut Canyon fault system; Lb—Leon buckle; Lm—Lukachukai monocline; Ma—Mescalero arch; Mfs—Montosa fault system; Mlfs—Morenci lineament fault system; Nfs—Nacimiento fault system; Nsz—Nalda shear zone; Nm—Nutria monocline; Pf—Pajarito fault; PSb—Pecos Slope buckles; PPf—Picuris-Pecos fault; RLfs—Red Lake fault system; RRm—Red Rock monocline; RPfs—Rio Puerco fault system; Rfs—Ruidoso fault system; SHf—Sand Hill fault; SCff—Sangre de Cristo frontal faults; TCfs—Tijeras-Cañoncito fault system; Tf—Tinnie fold belt; TPfs—Tusas-Picuris fault system; Vf—Vaughn fault; Wf—Winston fault. Well designations are: A—Humble Oil and Refining Co. No. 1 Santa Fe B; B—Shell No. 1 Santa Fe; C—Shell No. 3 Santa Fe; D—Shell West Mesa Federal 1–24; E—Southern Union Tijeras Canyon Unit No. 3; F—Shell Laguna–Wilson Trust #1; G—Shell No. 2 Santa Fe. Albuq.—Albuquerque.

TABLE 1. LARAMIDE DEXTRAL-OBLIQUE STRUCTURES IN CENTRAL AND NORTHERN NEW MEXICO

Name (map symbol, Fig. 1)	Evidence for dextral displacement	Estimated dextral offset	Other references
Borrego fault (Bf)	Shallowly plunging slickenlines (Bauer and Ralser, 1995; Moench et al., 1988; Ilg et al., 1997; P. W. Bauer, 1997, personal commun.)	N.D., but may be a southward extension of Tusas-Picuris fault which has ~15 km dextral offset	Karlstrom and Daniel (1993)
Chloride fault system (Clfs)	Horizontal slickenlines, orientation of R and R′ shears, flower structures, offset lithologic boundaries (Harrison, 1989)	3.1 km (Harrison, 1989)	Harrison (1990, 1994)
Chupadera fault (Cf)	North-northwest–trending shortening structures associated with restraining bend in T4S, R8,9E (S. M. Cather, unpub. data)	N.D.	Hawley (1986); Kelley and Thompson (1964); E. C. Beaumont, unpublished photogeologic map
Comanche fault system (Cfs)	Steeply plunging drag folds (Cabezas, 1991)	N.D., but may be a southward extension of Sand Hill fault (Kelley, 1977) which exhibits 20–33 km dextral offset	Callender and Zillinski (1976)
Defiance monocline (Dm)	Northwest-trending en echelon folds, offset Jurassic facies transition and pinch-out (Kelley, 1967)	13 km (Kelley, 1967)	Kelley (1955)
East Joyita fault (EJf)	Shallowly plunging slickenlines (Beck, 1993; Beck and Chapin, 1994)	N.D.	
Glorieta Mesa–Estancia Basin fault system (GMEBf)	Shallowly plunging slickenlines (Ilg et al., 1997; S. M. Cather, unpub. data; P. W. Bauer, 1996, personal commun.)	N.D.	
Hickman fault system (Hfs)	En echelon folds, shallowly plunging slickenlines, en echelon faults, southeast termination of Grants monocline (Cather and Johnson, 1986; Maxwell, 1986; Chamberlin et al., 1989, p. 31; Maxwell et al., 1989, p. 20–24)	N.D.	Wengerd (1959)
Hot Springs–Walnut Canyon fault system (HSWCf)	Offsets of Paleozoic and Mesozoic pinch-outs and facies, restraining-bend structures, shallowly plunging slickenlines (Harrison and Chapin, 1990; R. W. Harrison, 1996, personal commun.)	26 km (Harrison and Chapin, 1990); 0.5 km (Lozinsky, 1986; east strand only)	Nelson (1993)
Montosa fault system (Mfs)	Restraining-bend structures, releasing-bend structures, shallowly to moderately plunging slickenlines (Brown, 1987; Hayden, 1991)	N.D.	
Morenci lineament fault system (Mlfs)	Seismic-reflection imaging of positive flower structures (Kopacz et al., 1989; Garmezy et al., 1990)	N.D.	Cather and Johnson (1986)
Nacimiento fault system (Nfs)	En echelon growth folds that were active during Late Cretaceous–Eocene time (Baltz, 1967; K. G. Stewart, 1995, personal commun.; J. P. Hibbard,1995, personal commun.)	20–33 km (this study); 5 km (Baltz, 1967); 2 km (Woodward et al., 1992)	Kelley (1955); Woodward (1987)
Pecos Slope buckles (Psb)	Steeply plunging drag folds, en echelon folds and faults (Kelley, 1971)	N.D.	
Picuris-Pecos fault (PPf)	Offset Proterozoic structures and lithologies, large-scale drag folds, shallowly plunging slickenlines (Miller et al., 1963; Karlstrom and Daniel, 1993; Daniel et al., 1995; Bauer and Ralser; 1995; Ilg et al., 1997)	37 km (see text for discussion)	
Red Lake fault system (RLfs)	En echelon folds (Cather and Johnson, 1986)	N.D.	Wengerd (1959)
Rio Puerco fault system (RPfs)	Northeast-striking en echelon normal faults (Slack and Campbell, 1976)	<2 km (Slack and Campbell, 1976)	
Sangre de Cristo frontal faults	Northeast-striking dextral tear faults in frontal thrust faults (Baltz and O'Neill, 1984)	N.D.	O'Neill (1990)
Sand Hill fault (SHf)	En echelon normal faults (Rio Puerco fault system of Slack and Campbell, 1976); dextral offset of seaward limit of Gallup Sandstone (this study)	20–33 km (this study)	Kelley (1977); Cather et al. (1997)
Tijeras-Cañoncito fault system (TCfs)	Shallowly plunging slickenlines, en echelon folds (Abbott, 1995; Lisenbee et al., 1979; Chapin and Cather, 1981)	<10 km? (Kirby et al., 1995)	Kelley and Northrop (1975)
Tusas-Picuris fault system (TPfs)	Offset Proterozoic structures and lithologies (Karlstrom and Daniel, 1993; Daniel et al., 1995	15 km (see text for discussion)	
Winston fault (Wf)	En echelon folds, horizontal slickenlines, east-northeast R′ shears, positive flower structures (Harrison, 1994)	N.D.	

Note: N.D. = no data.

lines; or (2) geometric relationships with secondary structures (drag folds, en echelon folds and faults, faults and folds related to flower structures, and restraining or releasing bends). None of these types of data, however, provide information on the magnitude of lateral slip.

Identification of unambiguous piercing lines by which to constrain the magnitude of dextral displacements across Laramide faults has proven elusive. Well-documented dextral separations of Proterozoic structures and lithologic units in northern New Mexico have been interpreted as Laramide displacements (Chapin and Cather, 1981; Karlstrom and Daniel, 1993; Daniel et al., 1995). Because of the great antiquity of these Proterozoic piercing lines, however, the observed separations have not been demonstrated to be exclusively Laramide. Baltz (1967) used the apparent offset of axes of en echelon folds to estimate 5 km of Laramide dextral displacement along the Nacimiento fault system (Fig. 1). Woodward et al. (1992) argued that the correlation of fold axes across the Nacimiento fault system is ambiguous and therefore cannot be used to estimate lateral offset. Woodward et al. (1992) instead preferred the <2 km offset estimate of Slack and Campbell (1976) for the Rio Puerco fault system, a series of en echelon Laramide normal faults bounded on the east by the Sand Hill fault, a southward continuation of Nacimiento fault system. The estimation by Slack and Campbell (1976), however, was not based on piercing lines but on the summation of heave across en echelon faults of the Rio Puerco fault system. Their technique did not evaluate the potential for dextral displacement along the Rio Puerco faults or along the through going, north-striking Sand Hill fault. Kelley (1967) pioneered the use of Mesozoic pinch-outs and facies transitions as piercing lines to constrain Laramide dextral offsets and inferred ~13 km of dextral slip along the Defiance monocline, the limb of which is modified by numerous northwest-trending en echelon folds (Kelley, 1955, 1967).

Uncertainty as to the magnitude of dextral displacement across the eastern Colorado Plateau boundary has led to the development of widely disparate tectonic models for Laramide northward to northeastward motion of the Colorado Plateau relative to cratonic North America. Kelley (1955), Woodward (1974, 1976), and Woodward and Callender (1977) were the first to incorporate such Colorado Plateau motion in their Laramide tectonic models, although the magnitude of displacement was not specified. Of the numerous published models for regional Laramide deformation, only a few have attempted to estimate the amount of dextral offset across the eastern Colorado Plateau boundary in northern New Mexico. Based on a variety of techniques, these dextral offsets have been estimated variously to be 60–120 km (Chapin and Cather, 1981, 1983; based largely on estimated crustal shortening to the north of the plateau), 100–170 km (Karlstrom and Daniel, 1993; based on offset Proterozoic lithologic and structural features), ~100 km (Chapin, 1983; based on offset of magnetic anomalies), ~50 km (Daniel et al., 1995; based on offset of magnetic anomalies and of Proterozoic structural and lithologic features), 5–20 km (Woodward et al., 1997; based on their interpretation of Mesozoic stratigraphic features). Because of differences in the inferred position of the Euler pole for rotation of the Colorado Plateau relative to cratonic North America, Hamilton (1981, 1988) variously invoked moderate to small dextral displacements in the southern Rocky Mountains, based on inferred amounts of Laramide shortening to the north of the Colorado Plateau.

The following analysis utilizes regional Mesozoic isopach trends and pinch-out data to constrain the amount of lateral offset on Laramide faults in central and northern New Mexico. This method is particularly appealing in that it may allow estimation of lateral displacements of Laramide faults buried within the Rio Grande rift. A similar approach was employed by Woodward et al. (1997). Because of differences in methodology, however, their conclusions differ markedly from those of this study.

METHODS

Stratigraphic data from preorogenic deposits have been used in other areas to determine the magnitudes of lateral displacement in both ancient (Budnik, 1986) and active (Hill and Diblee, 1953; Graham et al., 1989) fault systems. Several caveats should be considered, however, when using such data. For example, mappable stratigraphic criteria such as isopach trends, lithologic pinch-outs, and lateral facies transitions are rarely linear over large distances. In this analysis, I use the term "deflection" in a nongenetic sense to denote nonlinear parts of isopach lines and pinch-out trends. Where a deflection occurs, it is important to consider the geographic distribution of control points that define the deflection in order to distinguish between curvature related to normal sedimentary processes (e.g., intrabasin subsidence patterns, along-strike variations in sediment supply) versus postdepositional tectonic offset. Figure 2A illustrates the interpretational ambiguity of a sedimentary pinch-out that has been offset by dextral faulting in an area of poor stratigraphic control. In this case, the broadly spaced control points can be contoured with a gently curving line that masks the actual abrupt offsets, and is thus permissive of either tectonic or sedimentary interpretations of origin. In the contrasting case (Fig. 2B), where stratigraphic control points are closely juxtaposed about the dextral faults, the contoured pinch-out trend more faithfully depicts the actual fault offsets, and the distinction between sedimentary versus tectonic origins is less equivocal. The possibility remains, however, that the abrupt isopach deflections required by the control points in Figure 2B may have originated during syndepositional differential subsidence (dip slip) along precursors to the dextral faults. This possibility can be evaluated by examination of the strata in question for evidence of syndepositional tectonism (e.g., differential erosion or thickening, abrupt changes in paleocurrent directions or sedimentary facies) at control points near the faults. Figure 2B thus illustrates two important points. First, in order to confidently distinguish between tectonic and sedimentary origins for lateral deflections, the distance between control points bracketing a suspected oblique-slip fault must be similar to, or smaller than, the magnitude of the observed deflection. Instances where the control spacing greatly exceeds the magnitude of an observed deflection are typically ambiguous in origin (Fig. 2A). Second, accurate visualization of

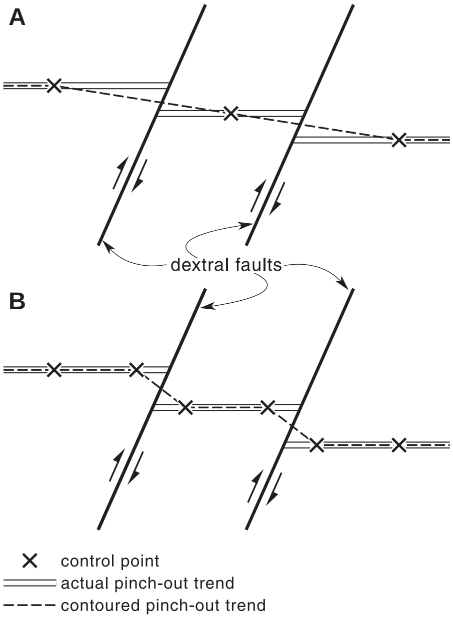

Figure 2. Schematic map of a dextrally offset pinch-out, showing effect of control-point spacing on interpretation of pinch-out deflections. (A) Widely spaced control points allow smooth contouring and thus are amenable to either sedimentary or tectonic interpretations of origin. Note that trend of pinch-out on middle structural block is undefined except by control points beyond bounding faults. (B) Closely spaced control points more faithfully depict the actual offsets. The presence of more than one control point on the middle structural block allows determination of pinch-out trend independent of control points beyond bounding faults.

TABLE 2. THICKNESS DATA FOR JURASSIC UNITS IN SUBSURFACE OF ALBUQUERQUE BASIN AREA

Stratigraphic unit	Thickness (m)					
	Humble Oil and Refining Co. No. 1 Santa Fe B	Shell No. 1 Santa Fe	Shell No. 3 Santa Fe	Southern Union Tijeras Canyon Unit No. 3	Shell Laguna-Wilson Trust No. 1	Shell No. 2 Santa Fe
Morrison Formation	250.9	153.9	286.6	189.0	160.4	0
Todilto Formation gypsum member	24.0	31.7	33.8	38.1	21.9	0
Todilto Formation limestone member	6.4	3.7	3.0	6.1	3.0	0
Entrada Sandstone	50.3	60.4	>41*	>22*	49.4	0

*Minimum thickness because total depth achieved within unit.

tectonic offsets in oblique-slip terranes requires knowledge of the trend of isopach lines, which necessitates the presence of two or more control points on each structural block. Because these conditions are rarely met, many of the observed dextral deflections of Mesozoic stratigraphic parameters in New Mexico are ambiguous in origin and thus may reflect stratigraphic and tectonic effects of unknown relative importance. Such deflections serve only to place maximum limits on possible tectonic offsets.

Of the Phanerozoic rocks in New Mexico, Mesozoic strata potentially contain the most definitive piercing-line data for Laramide offset. This is primarily because Mesozoic depositional systems older than about 80 Ma directly predated the Laramide orogeny and were only weakly influenced by local structural elements, thus limiting additional interpretive complications to those related to later Rio Grande rifting. Because available stratigraphic data for Triassic rocks in New Mexico are not sufficiently detailed to allow delineation of piercing lines, this analysis will be limited to strata of Jurassic and Cretaceous age. The use of pre-Early Permian data requires an accounting of strike-slip components related to the poorly understood ancestral Rocky Mountain deformation, during which north-striking faults in central New Mexico appear to have been mostly left-oblique normal (Beck and Chapin, 1994; Barrow and Keller, 1994; Karlstrom et al., 1997).

JURASSIC SYSTEM

Isopach patterns and pinch-out data are considered for three well-studied Jurassic units (Entrada Sandstone, Todilto Formation, and Morrison Formation) that are widely distributed in northern New Mexico. Data for this analysis were summarized largely from the literature (McKee et al., 1956; Ash, 1958; Lucas et al., 1985), although geophysical logs and cuttings from several petroleum exploration wells in the Albuquerque area were also used (Table 2; data are available at the New Mexico Library of Subsurface Data, New Mexico Bureau of Mines and Mineral Resources). The resulting maps were plotted on a base from Figure 1 that depicts known Laramide faults. This is not meant to imply that these faults were active during Jurassic time, but is simply intended to facilitate interpretation of possible Laramide lateral offsets vis-à-vis the Jurassic isopach patterns. These maps contain three types of information: (1) internal isopach data that depict thickness variations within preserved parts of each unit; (2) the location of Jurassic pinch-outs (zero isopach) where they are preserved or closely constrained; and (3) areas where Jurassic strata have been entirely removed by Tertiary erosion, within which the trend and location of isopach lines are interpretive.

There is good evidence for dextral offsets along the Defiance monocline (Kelley, 1967) and along the Sand Hill–Nacimiento fault system (see following). The more generalized Jurassic isopach maps of McKee et al. (1956) have been modified accordingly in these areas without compromising the control points. Because parts of the Sand Hill–Nacimiento fault system were active prior to Jurassic time (Woodward, 1996), syndepositional reactivation during Jurassic time may have contributed to the apparent isopach discontinuities in this area. Evidence for weak Jurassic syndepositional tectonism has been noted in areas to the west (Kirk and Condon, 1986) and east (Lucas et al., 1985) of the Sand Hill–Nacimiento fault system.

Entrada Sandstone

The Entrada Sandstone is an areally widespread eolian unit of Middle Jurassic age (Kocurek and Dott, 1983). The trend and location of the southward pinch-out of the Entrada (Fig. 3) are constrained in western New Mexico by outcrops ~40 km north of Quemado (O. J. Anderson, 1996, oral commun.) and in the Lucero uplift area 80 km southwest of Albuquerque (McKee et al., 1956). The Entrada Sandstone is not present in the Shell No. 2 Santa Fe well (Table 2) in the southwest part of the Albuquerque rift basin; the Entrada pinch-out therefore must be located to the north of this well.

The zero isopach is poorly defined in eastern New Mexico except ~30 km south-southwest of Tucumcari (Lucas et al., 1985), where its location is closely bracketed (Fig. 3). In the region between the Shell No. 2 Santa Fe well and the Tucumcari area, the trend and location of the Entrada zero isopach are imprecisely constrained within the broad area of Tertiary erosion southeast of Albuquerque. Given the absence of Jurassic strata between control areas near Socorro and Capitan on the south where the Entrada Sandstone is absent, and near Las Vegas, New Mexico, on the north where it is present, the Entrada data are permissive of interpretations of little or no Laramide offset (e.g., Woodward et al., 1997). Such interpretations, however, are not unique. Minor sinistral offsets are possible if the trace of the Entrada pinch-out passed close to the south of the Las Vegas area. If the zero isopach of the Entrada Sandstone passed close to the north of outcrops northeast of Socorro, where the Entrada is missing beneath the Morrison Formation, as much as ~60 km of right lateral displacement on Laramide faults in the Socorro and southern Albuquerque rift basins is possible (Fig. 3). Stepping eastward across the Montosa and Chupadera faults, outcrops where the Entrada Sandstone is missing beneath the Morrison Formation at Capitan allow cumulative dextral displacements of as much as ~110 km.

The internal (non-zero) isopachs of the Entrada Sandstone indicate substantially greater thicknesses in western New Mexico than in the eastern part of the state (Fig. 3). This relationship also holds true for the Todilto and Morrison Formations (see following), suggesting relatively greater subsidence on the Colorado Plateau than in eastern New Mexico during Middle and Late Jurassic time. There are no compelling correlations of internal isopachs of the Entrada Sandstone across the Sangre de Cristo uplift.

Todilto Formation

The Todilto Formation is of Middle Jurassic age and consists of a thin, widespread lower limestone member and a thicker, more areally restricted upper gypsum member. In southern Colorado, these strata are called the Pony Express Limestone. The Todilto Formation has been variously interpreted to have been deposited in a marine embayment or in a lake or salina (Kocurek and Dott, 1983; Lucas et al., 1985; Kirkland et al., 1995).

Depositional pinch-outs of the limestone and gypsum members of the Todilto Formation are preserved locally. This contrasts with the other Jurassic units considered in this report (Entrada and Morrison Formations), the zero isopachs of which are defined typically by erosional truncation beneath younger Mesozoic units.

The limestone member of the Todilto Forma-

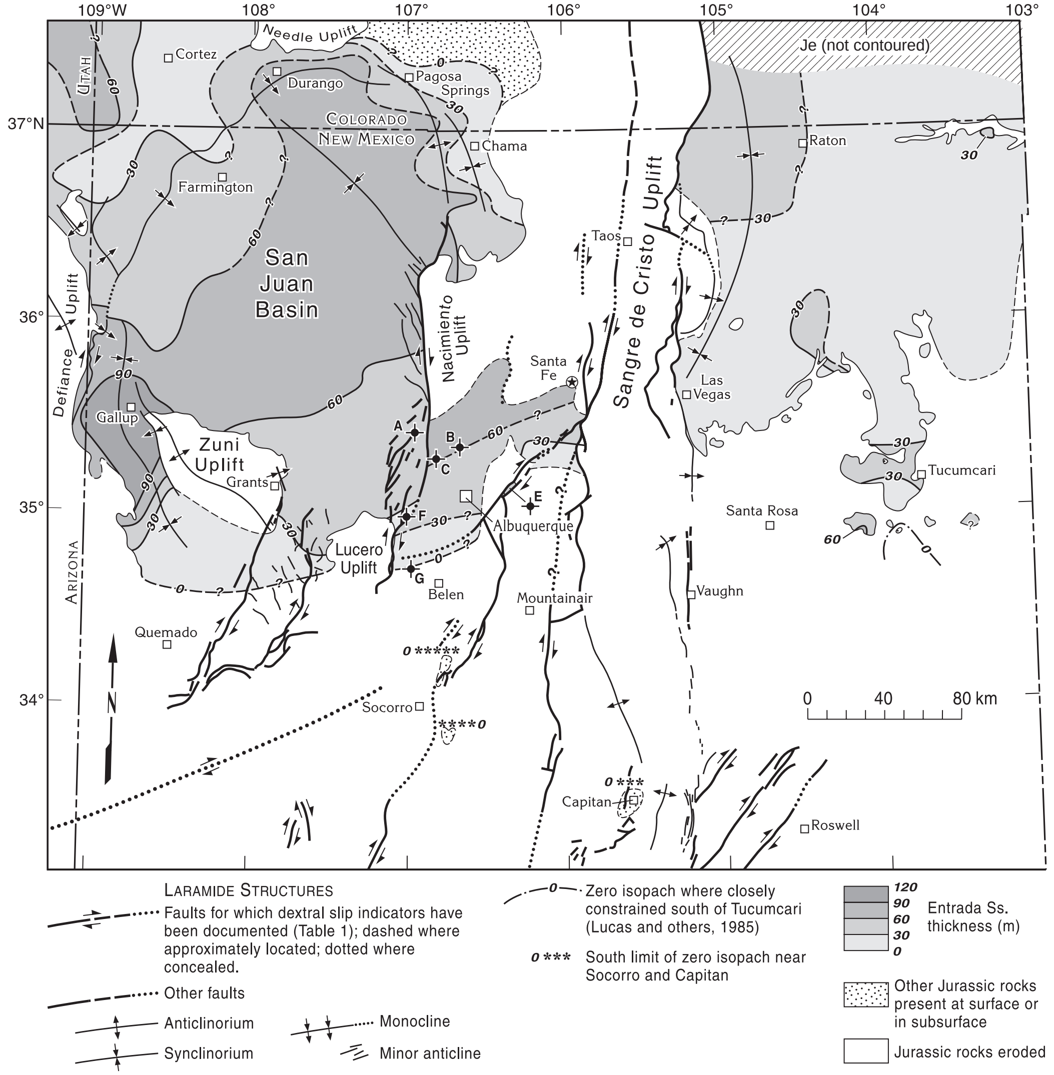

Figure 3. Isopach map of the Jurassic Entrada Sandstone. Data sources are McKee et al. (1956) (western New Mexico), Lucas et al. (1985) (eastern New Mexico), and well data near Albuquerque (Table 2). Laramide faults and well designations are from Figure 1. Je—Entrada Sandstone.

tion ranges from 0 to about 13 m thick (Fig. 4). The southern depositional pinch-out is well defined in western New Mexico, but was eroded during Tertiary time in a broad region southeast of Albuquerque. The southeastern depositional limit of the limestone member of the Todilto Formation is exposed in the Bull Canyon–Luciano Mesa area ~40 km southwest of Tucumcari, New Mexico. There, the eastern depositional pinch-out has been variously interpreted as sinuous and northeast trending (Lucas et al., 1985, Fig. 8), or relatively linear and northwest trending (Lucas and Kietzke, 1986, Fig. 1). Early regional studies (McKee et al., 1956; Ash, 1958) depicted a simple, relatively linear southern limit of Todilto limestone deposition, based on the ~300 km extrapolation between the pinch-out control points exposed near Bull Canyon on the east and in the western Lucero uplift on the west. The Shell No. 2 Santa Fe well constrained the southern limit of the pinch-out of the Todilto limestone along the east side of the Lucero uplift and thus narrows this interpretive gap to about 250 km (Fig. 4). Subsequent workers (e.g., Kocurek and Dott, 1983; Lucas et al., 1985; Kirkland et al., 1995; Woodward et al., 1997) continued to depict a relatively linear east-west–trending southern depositional limit for the limestone member in Jurassic paleogeographic maps, although long-standing evidence for Laramide oblique-slip faulting in the southern Rocky Mountains renders such simplistic interpretations suspect. The broad north-south constraints on the position and trend of the southern pinch-out of the limestone member are similar to those described here for the Entrada Sandstone, and provide similar limitations on lateral slip.

The northeast depositional limit of the limestone member is reasonably well defined near Las Vegas, New Mexico (Fig. 4). The northeastern Todilto pinch-out in Colorado is located about 45 km northeast of Pagosa Springs, where it is bracketed between the Champlin Petroleum 1 Federal 24-A1 well and the Amoco Beaver Mountain Unit 1 well (R. R. Gries, 1997, oral commun.; see Gries et al., 1997, for well locations). Between the Pagosa Springs and Las Vegas areas, the pinch-out is dextrally deflected ~70 km (Fig. 4). Because of the broad spacing of control points, however, it is not clear if the observed deflection is of sedimentary or tectonic origin, or both.

The gypsum member of the Todilto Formation was deposited in an elongate, north-trending basin. Although the isopach data in Figure 5 are somewhat smoothed because deposition occurred in numerous small brine pools (O. J. Anderson, 1996, oral commun.), the gypsum member generally thickens to the south and east. The gypsum member is not present south of the Tijeras-Cañoncito fault system or east of the Picuris-Pecos fault. The abrupt southeast limit of Todilto gypsum deposition suggests Jurassic northwest-down deformation along a precursor to the Tijeras-Cañoncito system, although additional effects of Laramide oblique-slip juxtaposition cannot be ruled out.

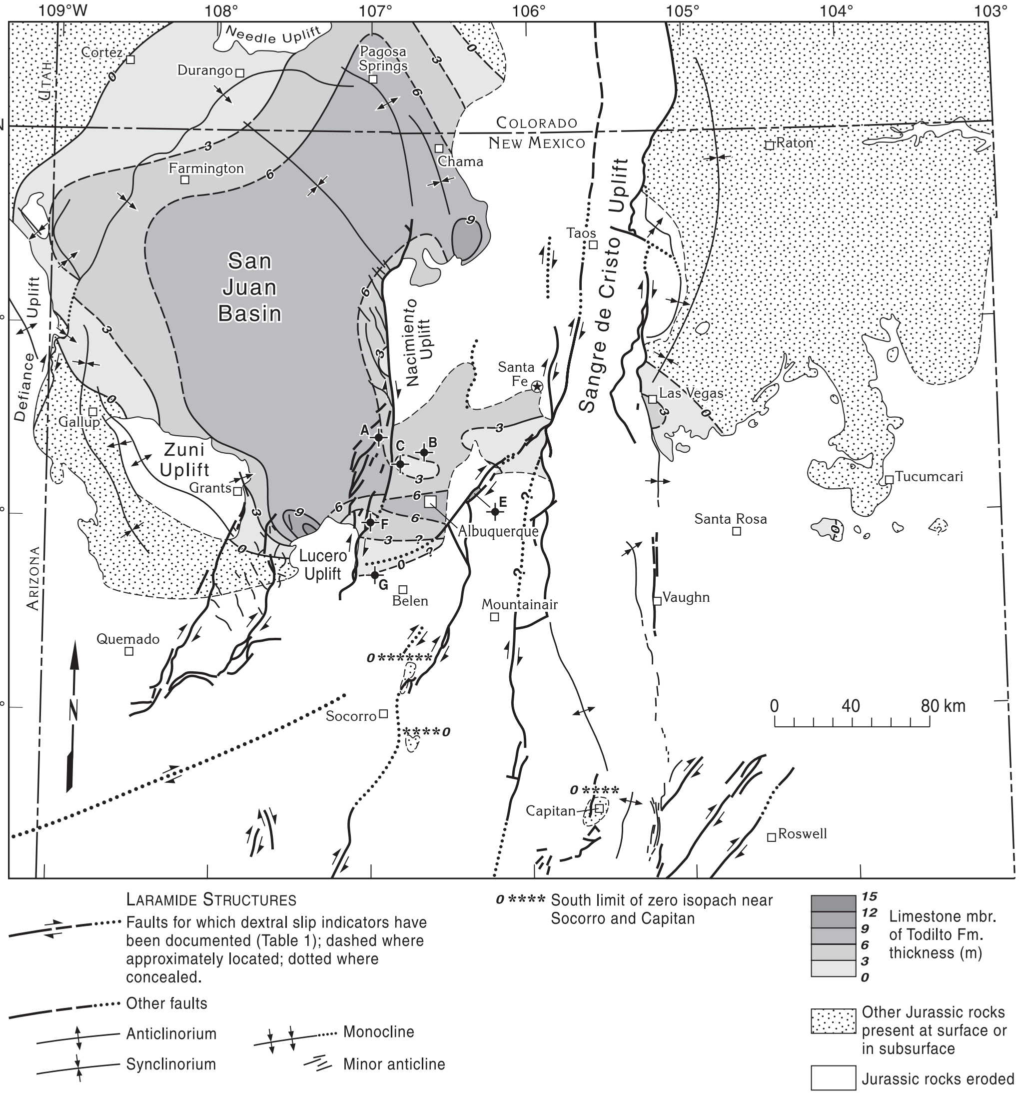

Figure 4. Isopach map of the limestone member of Jurassic Todilto Formation. Data sources are Ash (1958), Lucas et al. (1985), Baltz and O'Neill (1984), and well data near Albuquerque (Table 2). Laramide faults and well designations are from Figure 1.

Morrison Formation

The Upper Jurassic Morrison Formation is of fluvial-lacustrine origin and is broadly distributed throughout the Rocky Mountain area (Peterson, 1972). In western New Mexico, the southern limit of the Morrison Formation (Fig. 6) is somewhat north of that of the subjacent Entrada Sandstone, due to the effects of the southward beveling of both units beneath the Dakota Sandstone. The opposite relations prevail in outcrops near Socorro and Capitan, where the Morrison Formation is present but the Entrada Sandstone is not. These relations indicate that the position of the now-eroded pinch-out of the Entrada Sandstone in eastern New Mexico was north of these southernmost Morrison Formation outcrops and was determined by pre-Morrison erosion. Because the outcrops near Socorro and at Capitan are upper Morrison Formation (Brushy Basin Member; Lucas, 1991), it appears that in eastern New Mexico the Morrison onlapped its eroded southern basin margin late in its depositional history.

The zero isopach of the Morrison Formation is well defined in western New Mexico and passes north of the Shell No. 2 Santa Fe well (Black, 1979; Molenaar, 1988). The southern pinch-out is also closely constrained about 30 km south-southeast of Tucumcari (Fig. 6), where the Morrison Formation has been erosionally truncated beneath Cretaceous strata (Lucas et al., 1985, p. 237). Most previous studies (e.g., McKee et al., 1956; Peterson, 1972) have depicted a simple east-west Morrison basin margin that connects the pinch-outs exposed near Tucumcari to those in the Lucero uplift areas. Recent documentation of thin (<19.5 m) Morrison Formation deposits near Socorro (Hunt and Lucas, 1987; Hayden et al., 1990) and at Capitan (Lucas, 1991), however, requires that the location of the Morrison pinch-out in eastern New Mexico be much farther south. As summarized by Lucas (1991, p. 41), "The Capitan Morrison strata closely resemble the strata identified in Socorro County as Morrison by Hunt and Lucas (1987) and Hayden et al. (1990), but they are thicker. It seems most reasonable to view the outcrop at Capitan as a thin, truncated remnant of the Morrison Formation (Brushy Basin Member) that was deposited near the extreme southern edge of the Morrison depositional basin."

Figure 6 depicts the northern limit of the zero isopach as required by the erosional remnants of Morrison exposed near Capitan and Socorro. Assuming that the regional trend of the southern margin of the Morrison basin was approximately east-west in New Mexico, then a minimum ~60 km dextral deflection is required between the Shell No. 2 Santa Fe well and the Morrison outcrops northeast of Socorro. This abrupt deflection is relatively closely constrained to occur within the Socorro and southern Albuquerque basins of the Rio Grande rift. Laramide dextral faults that may have contributed to this deflection

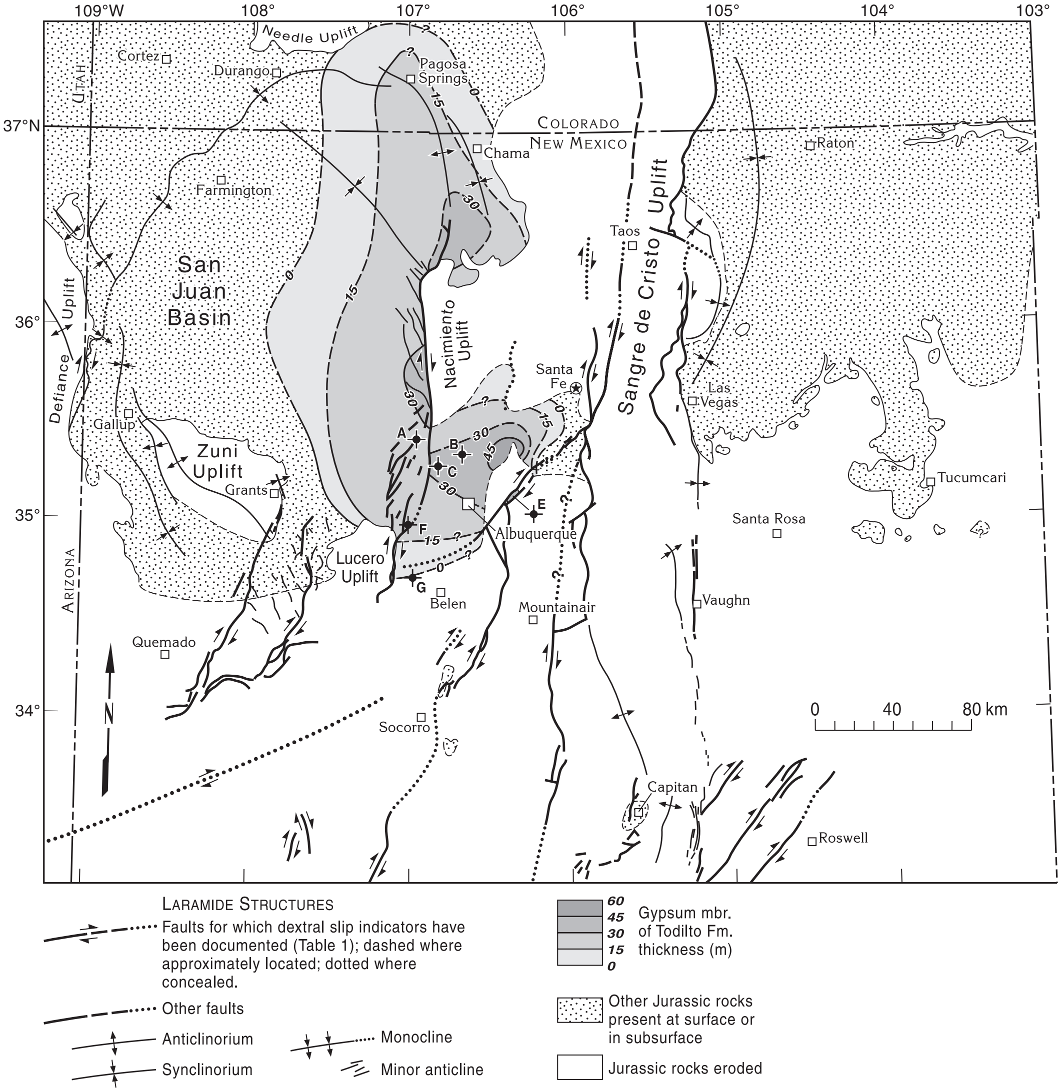

Figure 5. Isopach map of the gypsum member of Jurassic Todilto Formation. Data sources are Ash (1958) and well data near Albuquerque (Table 2). Laramide faults and well designations are from Figure 1.

are thus buried within the rift. Stepping eastward from Socorro across the Montosa and Chupadera faults, the minimum deflection increases to about 90 and 120 km, respectively (Fig. 6). Because of fragmentary exposure of the Morrison Formation in the Socorro and Capitan areas, however, it is not possible to distinguish between sedimentary versus tectonic components of the observed dextral deflections. Certainly the apparent onlapping nature of the upper Morrison Formation (Brushy Basin Member) in these areas would argue that at least part of the observed deflection is due to this late episode of southward depositional encroachment. However, the spatial coincidence between the observed deflection and known Laramide oblique-slip structures suggests a significant, but unknown, tectonic component.

Thickness trends and average grain size in the Morrison Formation differ from west to east across New Mexico. West of the Picuris-Pecos fault and its southern bifurcations the Morrison Formation is thick (locally >275 m) and dominated by east-west isopach trends (Fig. 6). East of the Picuris-Pecos fault the Morrison Formation is thin and is characterized mostly by north-south isopach trends. In addition, the Morrison Formation to the west is significantly coarser than in eastern New Mexico (Peterson, 1972, Fig. 8). These depositional distinctions probably explain the lack of compelling east-west correlation of internal isopachs within the Morrison Formation.

CRETACEOUS SYSTEM

Late Cretaceous sedimentation in northern New Mexico was characterized by transgressive-regressive cycles (Fig. 7). The details of sedimentation within these cycles are the subject of a voluminous literature, and are beyond the scope of this paper. Molenaar (1983a) recognized five regressive sequences of Late Cretaceous age in northern New Mexico and southern Colorado: He referred to these as, from oldest to youngest, R-1 through R-5 (Fig. 7). The four older regressions were followed by transgressions (T-2 through T-5) that terminated the seaward (northeastward) progradation of the regressive sandstones. The resulting seaward limits of each of these four regressive sandstones trend at moderate to high angles to Laramide structures in New Mexico and thus have the potential to serve as piercing lines.

The following analysis builds on the earlier work of Molenaar (1973, 1983a, 1988) and Black (1979, 1983), who depicted the regional pinch-out trends of Upper Cretaceous regressive sandstones in New Mexico for the purpose of stratigraphic analysis and/or petroleum exploration. Unfortunately, these pinch-out trends are too generalized to provide useful piercing lines for structural analysis.

The seaward pinch-out of regressive sandstones within marine mudstones is relatively easy to locate both in outcrop and in the subsurface (Table 3). The principal source of ambiguity in delimiting the seaward extent of regressive sand-

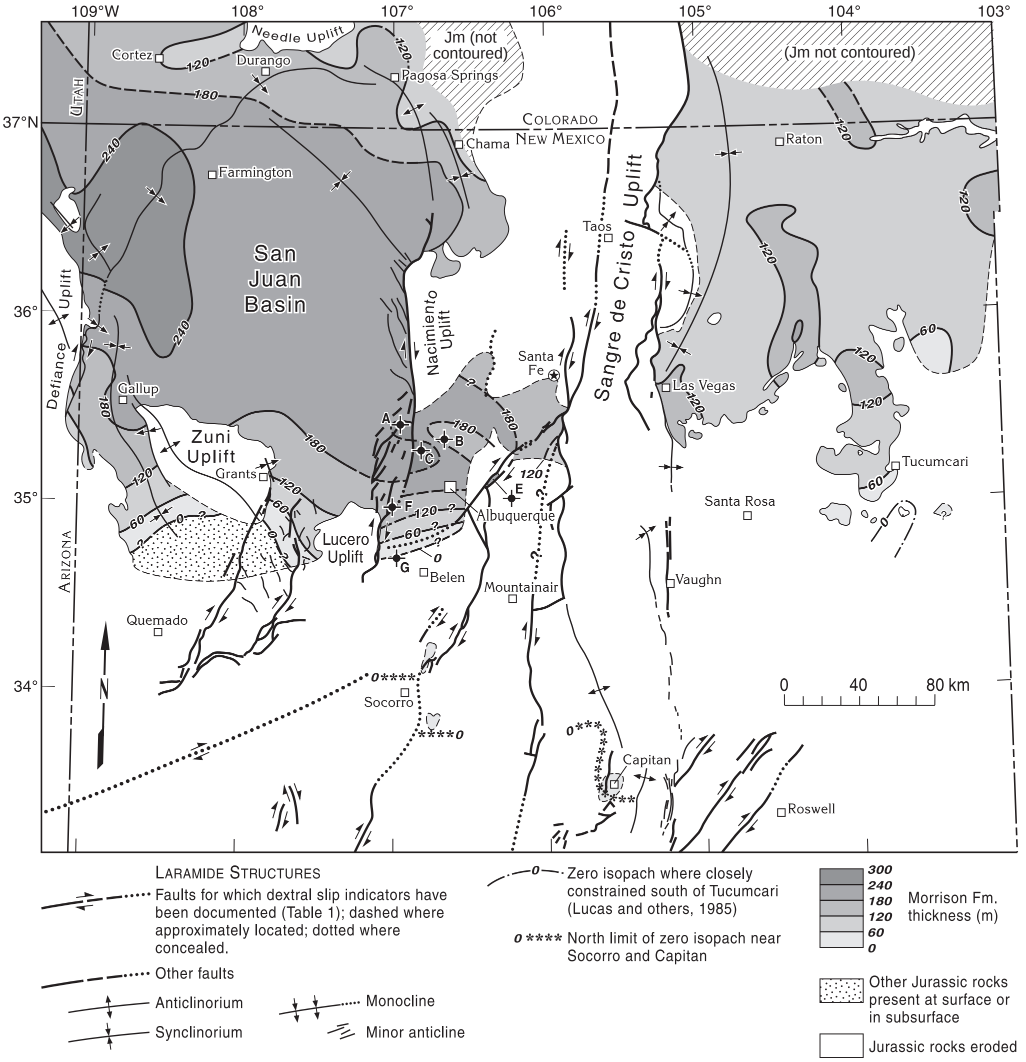

Figure 6. Isopach map of the Jurassic Morrison Formation. Data sources are McKee et al. (1956) (western New Mexico), Lucas et al. (1985) (eastern New Mexico), Lucas (1991), Hunt and Lucas (1987), Hayden et al. (1990) (Morrison outcrops near Capitan and Socorro), and well data near Albuquerque (Table 2). Laramide faults and well designations are from Figure 1.

stones is the local presence of offshore marine sandstone units at similar stratigraphic levels (e.g., Tocito Sandstone, Semilla Sandstone; Fig. 7). Such marine sandstones, however, can usually be identified by their laterally discontinuous nature and common upward-fining textures (Molenaar, 1974, 1977). Although not attempted in this study, the landward limits of transgressive marine units (T-1 through T-5, Fig. 7) potentially also could serve as piercing lines (see generalized trends in Molenaar, 1983a). The common juxtaposition of transgressive marine shales against underlying fine-grained continental deposits without intervening shoreface sandstones (Fig. 7) creates the potential for ambiguities in subsurface interpretation.

Tres Hermanos Formation (R-1)

The Tres Hermanos Formation is of Turonian age and consists of a lower regressive coastal-barrier sandstone (Atarque Member), a medial nonmarine, coastal-plain unit (Carthage Member), and an upper transgressive barrier-island sandstone (Fite Ranch Member; Molenaar, 1983a). The location and trend of the seaward limit of the Tres Hermanos are well defined by outcrops near Gallup and west of the Zuni uplift (Fig. 8, Table 3; Molenaar, 1973, 1983a). Eastward from the Zuni uplift, the pinch-out location becomes increasingly loosely bracketed by control points and the trend of the pinch-out on individual structural blocks is not defined. Assuming continuation of the trend defined in the Gallup-Zuni uplift area to the west, the pinch-out must deflect south (i.e., dextrally) of the Shell No. 2 Santa Fe well, in which the Tres Hermanos Formation is missing (Black, 1979; Molenaar, 1988), and pass north of outcrops in the Sevilleta area (control point K, Fig. 8; Baker, 1981). A dextral deflection of 10–60 km is thus indicated across what is now the southern Albuquerque rift basin. The broad spacing of pinch-out control points, however, allows both step-wise (Fig. 8) and smooth (e.g., Woodward et al., 1997, Fig. 7) contouring of the data, and thus renders ambiguous the determination of tectonic versus sedimentary origins for this deflection.

Gallup Sandstone (R-2) and Basal Niobrara (Tocito) Sandstones

The Gallup Sandstone is a regressive strandplain succession (Nummedal and Molenaar, 1995) that was deposited during a local regression only in New Mexico and northeastern Arizona (Molenaar, 1983a). The Gallup is upper Turonian–lower Coniacian in age (ca. 89 Ma; Nummedal and Molenaar, 1995), and thus was deposited <10 m.y. prior to the beginning of the Laramide orogeny. The Gallup Sandstone differs from the other regressive sandstones discussed in this report in that its seaward termination is in most places defined by erosional truncation beneath sandstones and shales of the basal Niobrara transgressive sequence (Fig. 7). Only in the Mesa Prieta area southwest of the Nacimiento uplift (Molenaar, 1974) and in the subsurface of the Albuquerque rift basin does the Gallup Sandstone show evidence for a simple depositional "turnaround" similar to that of the other regressive-transgressive sequences.

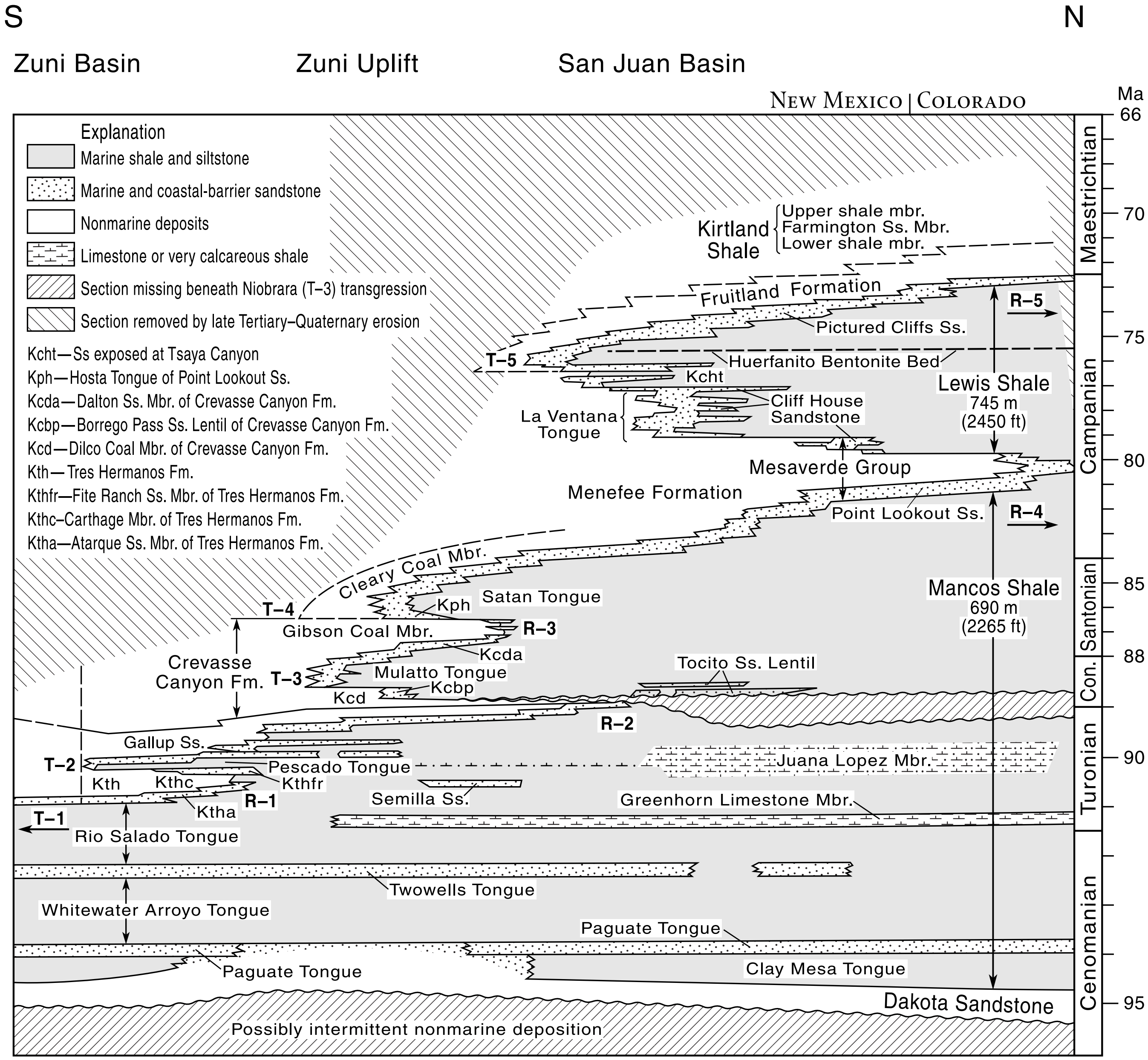

Figure 7. Schematic time-stratigraphic cross section of Cretaceous strata along a north-south line through the Zuni uplift–San Juan basin area. Modified from Molenaar (1983a).

The seaward limit of the Gallup is exposed in the Four Corners area west of Farmington, New Mexico (Molenaar et al., 1996), and is closely bracketed by well penetrations in the south-central and southeastern San Juan basin (Fig. 8; Table 3; Molenaar, 1973, 1974). These control points define a linear, southeast trend that is deflected sinistrally by the control point (H, Fig. 8) near the Nacimiento uplift. The more northeastward position of this control point relative to the trend defined in the San Juan basin probably reflects the lack of southwestward beveling beneath the erosive base of the T-3 (Niobrara) transgressive deposits in this area, and thus is not tectonic in origin. The approximate pinch out of the Gallup Sandstone is exposed along the pipeline road 4 km northeast of Mesa Prieta (Fig. 9), where the Gallup is only 1 m thick.

To the southeast, the seaward limit of the Gallup Sandstone steps abruptly to the right across the Sand Hill–Nacimiento fault system. This sharp dextral deflection is required by the absence of the Gallup Sandstone in the Shell No. 1 Santa Fe and Shell No. 3 Santa Fe wells, as documented by Black (1979) and Molenaar (1988) (Fig. 9). The Gallup is present in the Shell 1-24 West Mesa Federal well, where it constitutes a 21.3-m-thick upward-coarsening sequence. The seaward pinch out of the Gallup Sandstone is thus bracketed by the Shell No. 3 Santa Fe and Shell 1-24 West Mesa Federal wells, which necessitates a sharp dextral deflection of 20 to 33 km in the pinch-out trend as defined to the northwest in the San Juan basin (Fig. 8). This dextral deflection is compatible with the ~25 km dextral deflection of basement-related aeromagnetic trends in the Nacimiento uplift area, which was ascribed to Laramide strike-slip faulting by Karlstrom and Daniel (1993).

The control points near Mesa Prieta and in the western Albuquerque basin closely straddle the Sand Hill–Nacimiento fault system. The

TABLE 3. CONTROL POINTS FOR SEAWARD LIMITS OF UPPER CRETACEOUS REGRESSIVE SANDSTONES IN NORTHERN NEW MEXICO, SOUTHERN COLORADO, AND EASTERN ARIZONA

Unit and regression number	Control point	Location					Remarks
		Section	Township	Range	County	State	
Tres Hermanos Formation (R-1)	24	SE/4 30	26N	31	Apache	AZ	Exposure of approximate pinch-out.
	28A	NE/4 29	15N	19W	McKinley	NM	Exposure of approximate pinch-out.
	32A	NW/4 31	13N	16W	McKinley	NM	Exposure of approximate pinch-out.
	61B	SW/4 29 to NE/4 31	9N	8W	Cibola	NM	Bracketing exposure where Tres Hermanos is present.
	53B	SW/4 4	10N	7W	Cibola	NM	Bracketing exposure where Tres Hermanos is absent.
	G	29	6N	1W	Valencia	NM	Bracketing well (Shell Santa Fe No. 2) where Tres Hermanos is absent.
	K	9	1N	2E	Socorro	NM	Bracketing exposure (Baker, 1981) where Tres Hermanos is present.
Gallup Sandstone (R-2)	6	E/2 20	30N	19W	San Juan	NM	Exposure of approximate pinch-out.
	106	23	23N	12W	San Juan	NM	Bracketing well (Humble Oil and Refining No. 2) where Gallup is present.
	107	29	24N	11W	San Juan	NM	Bracketing well (Magnolia Petroleum No. 1) where Gallup is absent.
	120	25	16N	5W	McKinley	NM	Bracketing well (Hughes and Hughes No. 1) where Gallup is present.
	121	29	17N	4W	Sandoval	NM	Bracketing well (Refiners Petroleum No. 1) where Gallup is absent.
	H	NW/4 36	16N	2W	Sandoval	NM	Exposure of approximate pinch-out.
	B	28	13N	1E	Sandoval	NM	Bracketing well (Shell Santa Fe No. 3) where Gallup is absent.
	D	24	11N	1E	Bernalillo	NM	Bracketing well (Shell West Mesa Federal 1-24) where Gallup is present.
Hosta-Dalton (R-3)	105	18	21N	12W	San Juan	NM	Bracketing well (Sinclair Oil and Gas No. 1) where Hosta-Dalton is absent.
	104	26	20N	13W	McKinley	NM	Bracketing well (Sinclair Oil and Gas No. 1) where Hosta-Dalton is present.
	121	29	17N	4W	Sandoval	NM	Bracketing well (Refiners Petroleum No. 1) where Hosta-Dalton is absent.
	120	25	16N	5W	McKinley	NM	Bracketing well (Hughes and Hughes No. 1) where Hosta-Dalton is present.
	J	W/2 24	17N	2W	Sandoval	NM	Exposure of approximate pinch-out.
	L	31	14N	6E	Sandoval	NM	Exposure of approximate pinch-out.
Point Lookout Sandstone (R-4)	I	33	36N	1W	Archuleta	CO	Exposure of approximate pinch-out (O. J. Anderson, 1997, personal commun.).

Notes: Control points designated by single letter are from this study. All others are from Molenaar (1973, 1974, 1983a) and Molenaar et al. (1996). Locations are projected where surveys are incomplete. AZ—Arizona; NM—New Mexico; CO—Colorado.

Nacimiento fault system that forms the western boundary of the Nacimiento uplift has long been recognized as a Laramide dextral-oblique structure (Kelley, 1955), primarily due to an adjacent series of northwest-trending, en echelon growth folds that developed synchronously with Laramide sedimentation in the eastern San Juan basin (Baltz, 1967). Although the linear trace and the association with secondary en echelon structures suggest that the Sand Hill–Nacimiento fault system accommodated most or all of the observed dextral offset, the possibility remains that Laramide precursors to faults east of the Nacimiento uplift (Fig. 9) also may have participated.

Southward along strike of the Nacimiento fault system is the Sand Hill fault (Fig. 9), which is currently an intrarift fault that cuts and juxtaposes rift-fill deposits of differing ages (Kelley, 1977; Cather et al., 1997). The following relations, however, suggest that the Nacimiento and Sand Hill systems share a common Laramide ancestry. (1) Both fault systems mutually are on strike and dip steeply to the east. (2) The continuity of their traces has been demonstrated except in small areas of poor exposure or incomplete mapping (e.g., Santos, 1975; Anderson et al., 1997; Kelley, 1977; Cather et al. 1997). (3) The Sand Hill fault bounds the en echelon normal faults of the Rio Puerco fault system in a manner similar to that in which the Nacimiento fault bounds the en echelon folds of the eastern San Juan basin (Fig. 9). Although in part reactivated during rifting, the Rio Puerco faults were active as a Laramide dextral-oblique system (Slack and Campbell, 1976). (4) The Sand Hill fault has been traced to the southwest by Kelley (1977), where it splays into several intrabasin rift faults of unknown ancestry as well as the basin-margin Comanche fault system. The Charlie Hill fault within the Comanche fault system exhibits evidence of dextral slip of Laramide age (Cabezas, 1991, p. 33).

An origin for the pinch-out deflection of the Gallup Sandstone related to Gallup age dip-slip faulting is unlikely. At the exposed pinch-out northeast of Mesa Prieta (control point H, Figs. 8, and 9), the Gallup Sandstone shows no evidence of erosional truncation beneath overlying Niobrara transgressive deposits (Molenaar, 1974; O. J. Anderson, 1997, oral commun.), despite proximity to broad areas of erosively based Niobrara sequences in the San Juan basin (Molenaar, 1973, 1974) and in the Hagan basin (Black, 1979). Similarly, the Gallup Sandstone in the Shell 1–24 West Mesa Federal well shows no evidence of truncation beneath erosionally based, upward-fining transgressive deposits such as those typical of the basal Niobrara in the central and northwestern San Juan basin (Molenaar, 1974, p. 257–258). In view of the proximity to areas of post-Gallup erosion to the northwest and east, had the observed dextral deflection been the result of Gallup-age dip slip on the Sand Hill–Nacimiento fault system, it is unlikely that continuous sedimentation would have occurred on both the upthrown and downthrown blocks.

The Tocito Sandstone Lentil of the Mancos Shale comprises a series of oil-productive lenticular sandstones related to post-Gallup Sandstone erosion and the ensuing basal Niobrara transgression. The Tocito sandstones form an arcuate trend in the San Juan basin, and diverge eastward from the pinch-out trend of the Gallup Sandstone (Fig. 8, Molenaar, 1973, 1983b; cf. Woodward et al., 1997, Fig. 7). The Tocito sandstones are absent in the eastern San Juan basin (Molenaar, 1974) and have not been encountered by drilling in the Albuquerque basin. To the east, however, Tocito sandstones are exposed in the southern Hagan basin and in the Tijeras syncline (Black, 1979). These exposures are dextrally deflected ~100 km from the trend defined in the San Juan basin (Fig. 8). Be-

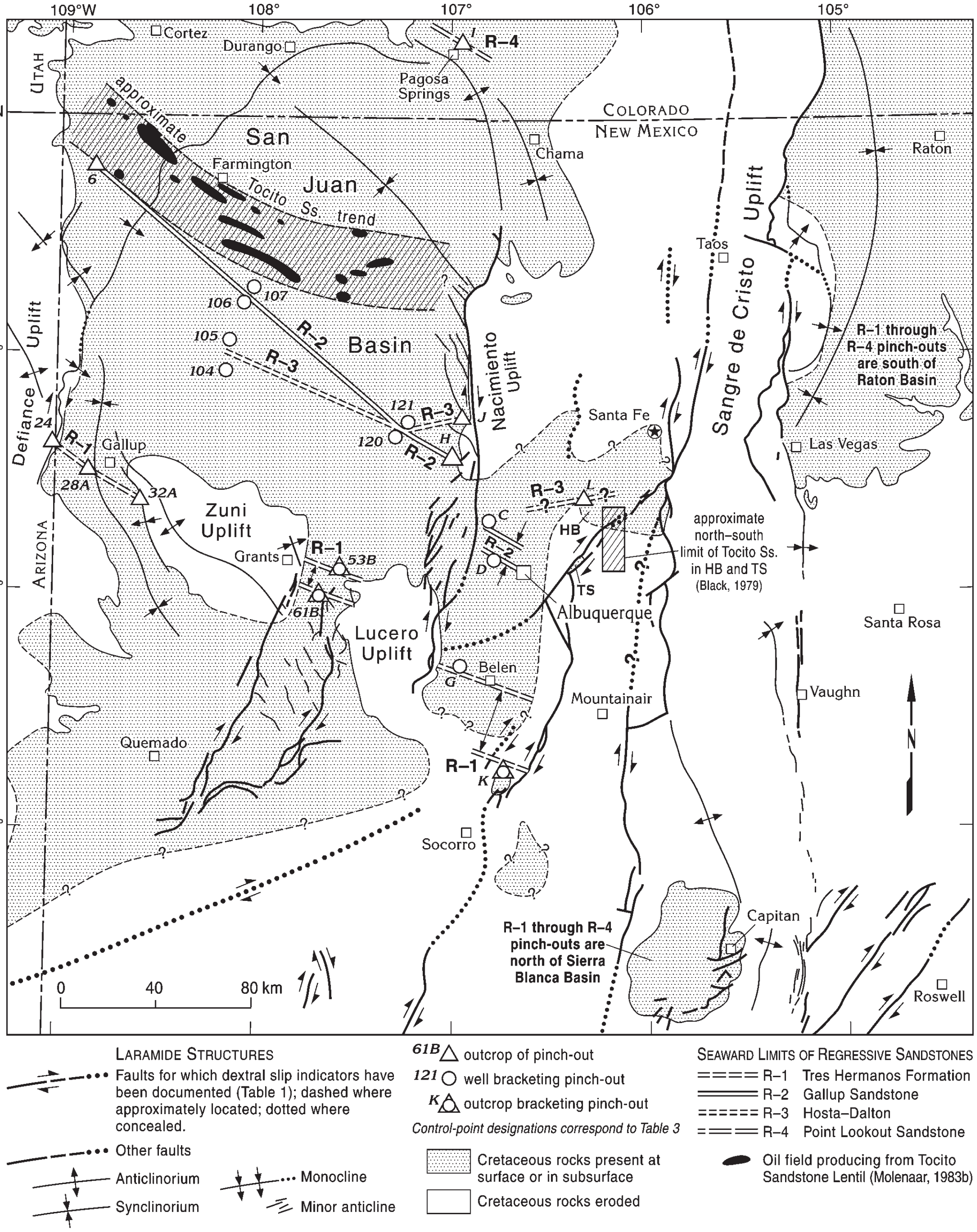

Figure 8. Map showing seaward limits of Upper Cretaceous regressive sandstones with control points (Table 3) and distribution of basal Niobrara (Tocito) sandstones. Laramide faults are from Figure 1. TS—Tijeras syncline; HB—Hagan basin.

cause of the unproven genetic link between Tocito sandstones in the Tijeras syncline–Hagan basin area to those to the northwest, as well as the absence of Tocito Sandstone in the Albuquerque and eastern San Juan basins, the apparent offset depicted in Figure 8 is of indeterminate origin.

Hosta-Dalton Sequence (R-3)

The R-3 regression is Santonian in age and is recorded by the Dalton Sandstone Member of the Crevasse Canyon Formation. The Dalton member is overlain by the transgressive Hosta Tongue of the Point Lookout Sandstone (Fig. 7; Molenaar, 1983a). In deposits near the seaward limit of the regression, Dalton and Hosta deposits become indistinguishable due to the lack of intervening continental deposits of the Crevasse Canyon Formation. In such “turnaround” areas, the term Hosta-Dalton is commonly used in the literature (e.g., Black, 1979, 1983). The seaward pinch-out of the Hosta-Dalton is closely bracketed by wells in the south-central and southeast San Juan basin (Molenaar, 1973, 1974, 1983a) and is exposed southwest of the Nacimiento uplift (Fig. 8; Table 3). The Hosta-Dalton pinch-out is located north of the array of deep petroleum tests in the Albuquerque basin and is again exposed in the Hagan basin area (Cano Sandstone of Stearns, 1953b) about 40 km northeast of Albuquerque (Fig. 8). The Hagan basin control point is dextrally deflected about 40 km relative to the Hosta-Dalton pinch-out trend defined to the west. The origin of this deflection (i.e., sedimentary vs. tectonic) is unclear, however, given the sparse, nonlinear control in the San Juan basin and the lack of subsurface control in the northern Albuquerque basin.

Point Lookout Sandstone (R-4)

The R-4 regression is represented by the Campanian Point Lookout Sandstone. The seaward pinch-out of the Point Lookout Sandstone crops out in southern Colorado near Pagosa Springs

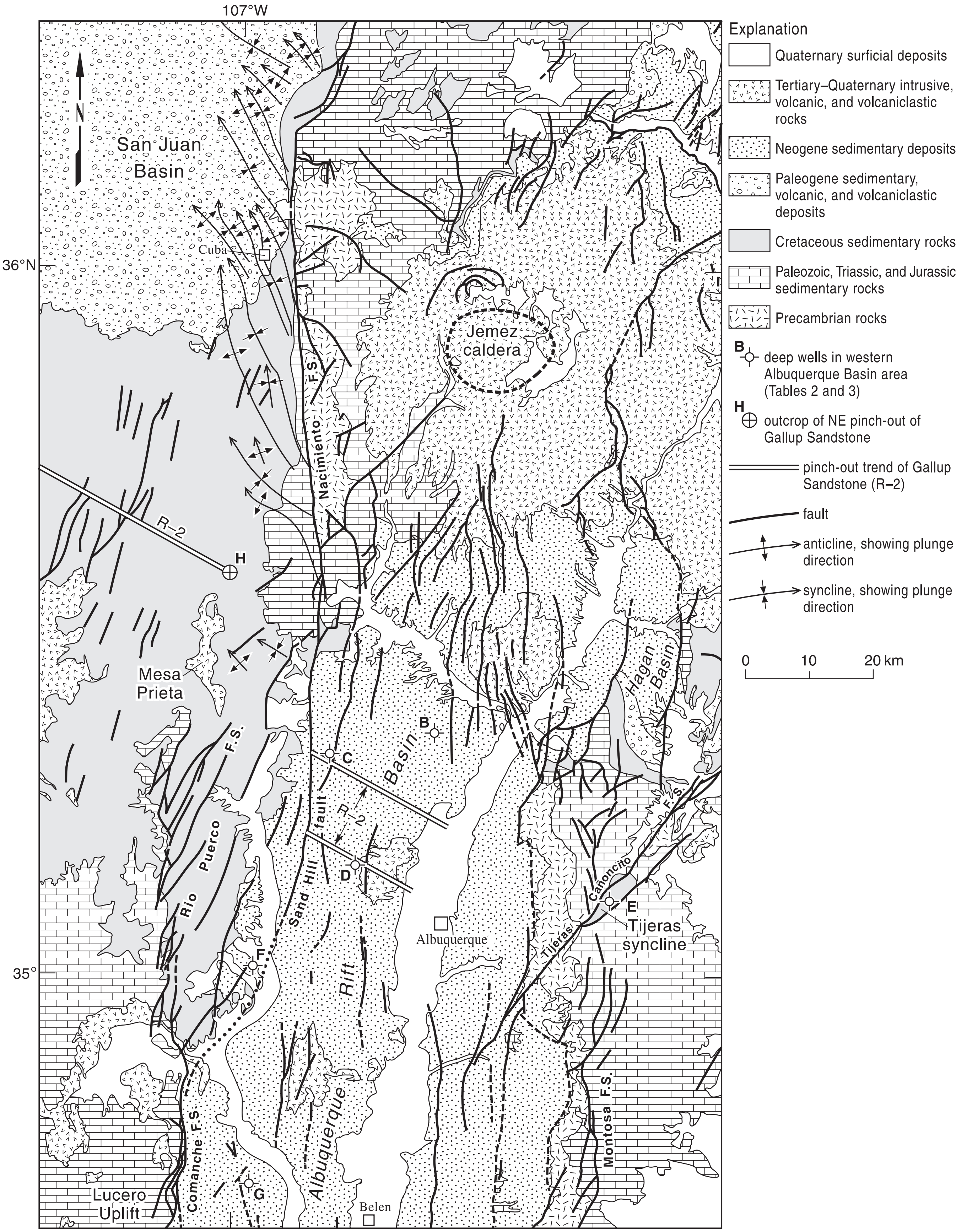

Figure 9. Geological map showing details of the Sand Hill–Nacimiento fault system and control points that constrain the offset of the Gallup Sandstone. Modified from Anderson et al. (1997), Kelley (1977), and Cather et al. (1997).

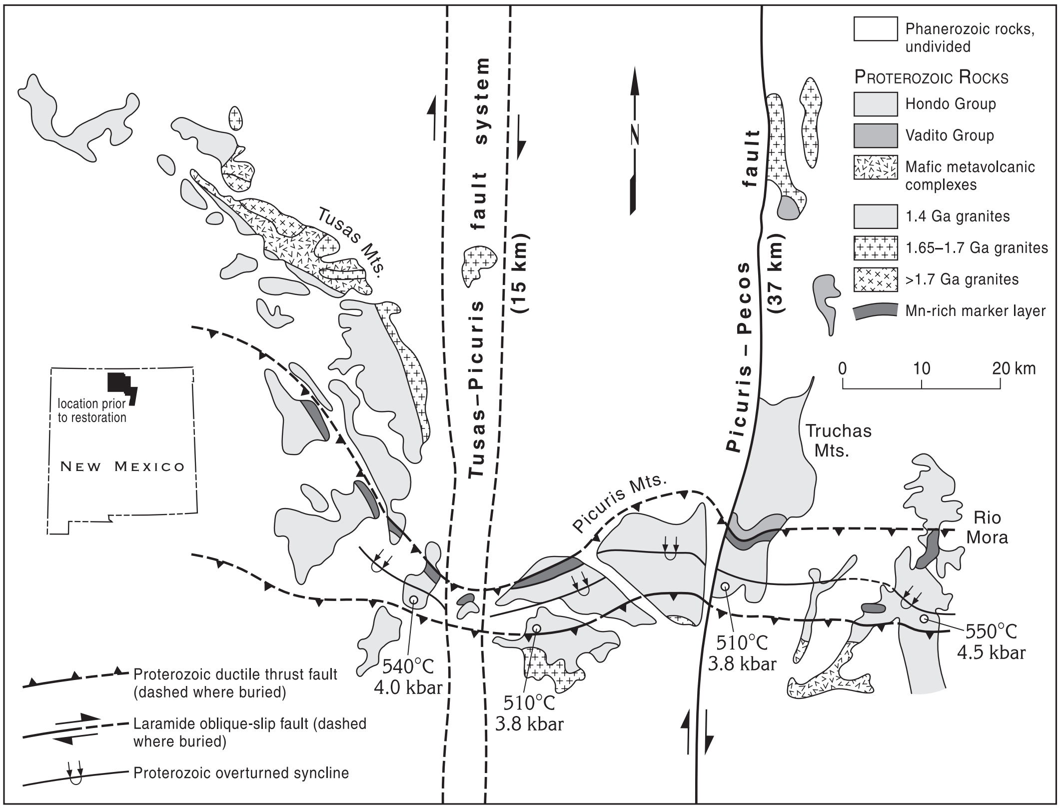

Figure 10. Map of reconstructed Proterozoic fold and thrust belt in north-central New Mexico (inset shows location of unreconstructed terrane) after removal of 15 km dextral slip on the Tusas-Picuris fault system and 37 km dextral slip on the Picuris-Pecos fault. Also shown are sample localities that demonstrate regionally similar peak-metamorphic temperatures and pressures. See text for discussion. Modified from Daniel et al. (1995).

(Fig. 8; Molenaar, 1983a, p. 220; O. J. Anderson, 1996, oral commun.). The trend of the pinch-out near Pagosa Springs is poorly defined, but is generally thought to be subparallel to the northwest trend defined by the pinch-out of related continental deposits of the Menefee Formation in southern Colorado and northern New Mexico (Fig. 7; Molenaar, 1983a, Fig. 10). Previously published maps depict the Point Lookout pinch-out crossing the Raton basin north of Las Vegas (Black, 1983, Fig. 3; Molenaar, 1983a, Fig. 10). The Point Lookout Sandstone, however, is not present in the Raton basin (Fassett, 1976; O. J. Anderson, 1996, oral commun.), and so a significant dextral deflection of the pinch-out trend to the southeast of the Pagosa Springs area is required. In eastern New Mexico the Point Lookout pinch-out shares similar broad geographic constraints with other (R-1 through R-3) regressive sandstones. These pinch-outs must pass south of the Raton basin and north of the Capitan area (Arkell, 1986). In view of these large uncertainties, a distinction between tectonic versus sedimentary origins for the Point Lookout deflection across the Sangre de Cristo–Rio Grande rift area is not possible.

DISCUSSION AND SUMMARY

Primarily because of regional differences in the distribution and quality of control points, the robustness of conclusions that can be drawn from the preceding analysis is locally variable. There are no well-constrained Mesozoic isopach data that uniquely support models calling for small (<20 km) dextral offsets along the eastern Colorado Plateau boundary in New Mexico (e.g., Hamilton, 1988; Woodward et al., 1997), although data for several of the more poorly constrained units are permissible of such interpretations. It is perhaps significant that all Jurassic and Cretaceous units examined either exhibit, or are permissive of, significant dextral deflections across the Rio Grande rift–southern Rocky Mountain area. In two cases (Defiance monocline and Sand Hill–Nacimiento fault system) Mesozoic stratigraphic criteria seem to provide definitive tectonic-offset constraints.

On a local scale, the best-constrained example of dextral tectonic offset is along the Sand Hill–Nacimiento fault system, where the seaward limit of the Gallup Sandstone is displaced 20–33 km. Two other Upper Cretaceous regressive sandstones also show dextral deflections across the Albuquerque basin area, but the origins of those deflections are not well determined. That the magnitude of the dextral tectonic offset of the Gallup pinch-out is compatible with dextral deflections exhibited by the seaward limits of the Tres Hermanos Sandstone (10–60 km) and the Hosta-Dalton sequence (~40 km) suggests a tectonic origin for at least part of these deflections as well. It is possible that the tectonic offset of the Tres Hermanos and Hosta-Dalton pinch-outs may exceed that observed for the Gallup Sandstone. This is because the Gallup Sandstone control points encompass only the western part of the Albuquerque basin, whereas those for the Tres Hermanos and Hosta-Dalton span the entire basin. Mesozoic pinch-out data suggest that the upper limit of allowable Laramide dextral offset across the Rio Grande rift is ~40 km near Albuquerque and ~60 km near Socorro.

Offset constraints by Mesozoic isopach data that span the breadth of the Laramide deformed zone in New Mexico are sparse, particularly for Laramide faults east of the Rio Grande rift. This is primarily because Cretaceous and Jurassic strata have been stripped by extensive Tertiary erosion southeast of Albuquerque. The seaward regressive limits of the Upper Cretaceous sandstones in eastern New Mexico are only loosely bracketed as having passed through the ~200-km-wide, erosionally stripped area south of the Raton basin and north of Cretaceous outcrops in the Sierra Blanca basin. The trend and location of the southern pinch-outs of the Entrada Sandstone and the limestone member of the Todilto Formation are so broadly bracketed as to allow interpretations ranging from small sinistral offsets to those that allow maximum cumulative dextral offsets west of the Capitan area of as much as ~110 km.

The only reasonably well defined Mesozoic isopach trends documented in this report that span most or all of the Laramide oblique-slip zone in northern and central New Mexico are the northeast basin margin of the limestone member of the Todilto Formation (Fig. 4) and the southern pinch-out of the Morrison Formation (Fig. 6). The northeastern zero isopach of the limestone member of the Todilto Formation exhibits a dextral deflection of ~70 km across the Sangre de Cristo uplift and the Rio Grande rift. The southern pinch-out of the Morrison Formation steps dextrally at least 120 km from near the latitude of Belen on the west side of the rift to the south of the latitude of Capitan near the east edge of the Laramide deformed zone. An unknown part of both of these deflections, however, may be sedimentary in origin.

To summarize, the Mesozoic data support at least 20 to 33 km of right-lateral offset across the Sand Hill–Nacimiento fault system. This is in addition to the 13 km offset described by Kelley (1967) in the Defiance monocline area, giving a combined minimum dextral offset of 33–46 km. Allowable dextral offsets across the rift may have been as much as 40 km near Albuquerque and 60 km at the latitude of Socorro. Considering the entire breadth of the Laramide deformed zone in central and northern New Mexico, Mesozoic data only provide generalized limits on possible displacement and allow as much as 110 km of dextral offset. These data suggest that the upper ranges of dextral Laramide displacements estimated by Chapin and Cather (1981; 60–120 km) and Karlstrom and Daniel (1993; 100–170 km) are too large. However, the Mesozoic data discussed in this report do not support the 5–20 km offset estimates of Woodward et al. (1997) or the minor strike-slip components implied by the central New Mexico Euler pole model of Hamilton (1988).

Due to the effects of Tertiary erosion, Mesozoic stratigraphic data fail to precisely constrain the limits of Laramide dextral offsets on faults east of the Rio Grande rift, particularly the prominent and episodically reactivated Picuris-Pecos fault and its southern bifurcations. The Picuris-Pecos fault is one of at least two faults that juxtapose dissimilar Proterozoic terranes in northern New Mexico (Fig. 10). As first noted by Miller et al. (1963), the Picuris-Pecos fault shows evidence for a 37 km dextral offset of Proterozoic lithologies (including a distinctive Mn-rich layer) and ductile structures. Using similar lines of evidence, Karlstrom and Daniel (1993) documented ~15 km of dextral offset of Proterozoic lithologies and structures across the Rio Grande rift in north-central New Mexico that they explained with a buried Laramide fault system (the Tusas-Picuris fault system, Fig. 1). The Proterozoic rocks exposed in the Tusas, Picuris, Truchas, and Rio Mora areas record relatively uniform pressure-temperature (*P-T*) conditions of 3.5–4.5 kbar and 500–550 °C (Fig. 10; Grambling and Williams, 1985; Grambling et al., 1989). Because these pressure differences of 0.5 to 1.0 kbar represent only 2 to 4 km differences in depth, the observed dextral separation of steeply dipping Proterozoic lithologic contacts, ductile thrusts, and axial planes of folds cannot be explained by dip-slip displacement alone (Daniel et al., 1995).

The origin of the net 37 km dextral offset present on the Picuris-Pecos fault has been variously interpreted. Miller et al. (1963) postulated a Proterozoic age for dextral displacement on the basis of perceived ductile rotation of foliation into the fault. Karlstrom and Daniel (1993), however, noted that the Picuris-Pecos fault is a brittle strike-slip feature that abruptly truncates Proterozoic foliations, an interpretation that is supported by local areas of brecciation along the fault (Miller et al., 1963; Bauer, 1988). Karlstrom and Daniel (1993) regarded the 37 km dextral offset to be mostly Laramide in origin. Chapin and Cather (1981) estimated ~26 km of Laramide dextral slip along the Picuris-Pecos based on their reinterpretation of a mismatch between Lower Pennsylvanian detrital assemblages and adjacent source terranes across the fault (Miller et al., 1963, p. 41). Subsequent studies have shown, however, that this apparent mismatch is the result of mineralogic changes due to diagenetic processes (Soegaard, 1990). Woodward et al. (1997) interpreted the dextral offsets on the Picuris-Pecos fault to be mostly Precambrian and/or late Paleozoic in age, despite the observation of Bauer and Ralser (1995, p. 114) of a dominance of shallowly plunging striae along the Picuris-Pecos fault and related faults in rocks as young as Mesozoic age.

By a process of elimination, a reasonable case can be made that the observed dextral fault offsets of Proterozoic rocks in northern New Mexico represent minimum Laramide offsets. Northern New Mexico has undergone three principal Phanerozoic deformations: (1) ancestral Rocky Mountain orogeny of Late Mississippian–Early Permian age; (2) Laramide deformation of Late Cretaceous–Eocene age; and (3) Rio Grande rift deformation of late Cenozoic age. Of these three known deformations, only the Laramide is compatible with large-scale brittle right-lateral fault offsets. The Rio Grande rift opened in a somewhat left-oblique fashion (Kelley, 1982; Chapin and Cather, 1994). North-striking late Paleozoic faults east of the Colorado Plateau are also sinistral (Beck and Chapin, 1994; Karlstrom et al., 1997; Barrow and Keller, 1994). Although pre-Pennsylvanian brittle deformation of unknown character is at least locally manifested in northern New Mexico (Bauer and Ralser, 1995), the only demonstrably Proterozoic right-lateral deformation is ductile (e.g., Grambling and Dallmeyer, 1993). The presence of Late Proterozoic dextral brittle faults in northern New Mexico cannot be ruled out, but no evidence for their existence has been found. It seems plausible that components of lateral slip during Late Proterozoic brittle faulting in this area would be sinistral, as would be necessary to accommodate extension in the Uinta aulacogen to the north of the Colorado Plateau. Thus, the cumulative brittle offsets observed on the Picuris-Pecos fault and Tusas-Picuris fault system (37 km and 15 km, respectively) may provide minimum estimates of Laramide dextral offsets because of the need to account for possible late Paleozoic and rift-related sinistral components.

IMPLICATIONS FOR LARAMIDE TECTONIC MODELS AND ROTATION OF THE COLORADO PLATEAU

Numerous tectonic models for regional Laramide deformation have invoked movement of the Colorado Plateau relative to cratonic North America (Sales, 1968; Hamilton, 1981, 1988; Chapin and Cather, 1981; Livaccari, 1991; Karlstrom and Daniel, 1993). Of these models, only those of Hamilton (1981, 1988) and Chapin and Cather (1981) attempted to quantify Laramide plateau motion in terms of Eulerian rotations. The net Laramide motion of the Colorado Plateau relative to cratonic North America can be approximated in Eulerian terms (i.e., the net motion of one plate relative to another on a sphere, expressed as a finite rotation about a specified pole of rotation). The nature of net Laramide deformation within the deformed area between the Colorado Plateau and cratonic North America (i.e., the central and southern Rocky Mountains) is a reflection of, and can be used to constrain, the Eulerian parameters of plateau rotation.

The central Rocky Mountain area to the north of the Colorado Plateau is characterized by major shortening across dominantly northwest-trending ranges and subsidiary left-lateral offsets along east-west structures. Estimates of the amount of crustal shortening in the central Rocky Mountains vary between about 5% and 15% (Kanter et al., 1981; Hamilton, 1981, 1988; Brown, 1988; Chapin and Cather, 1981; Gries, 1981). Perhaps the most detailed assessment of crustal shortening to the north of the Colorado Plateau is that of Stone (1993a), who calculated 8%–12% shortening along a well-constrained, northeast-trending transect between the western Green River basin and the Black Hills. Considering only those portions east of the Cordilleran thrust belt, the transect of Stone (1993a) is about 600 km long and, assuming 10% shortening, encompasses ~60 km of crustal shortening.

Using crustal shortening estimates for the monoclines of the Colorado Plateau and for the Uinta uplift in combination with the shortening

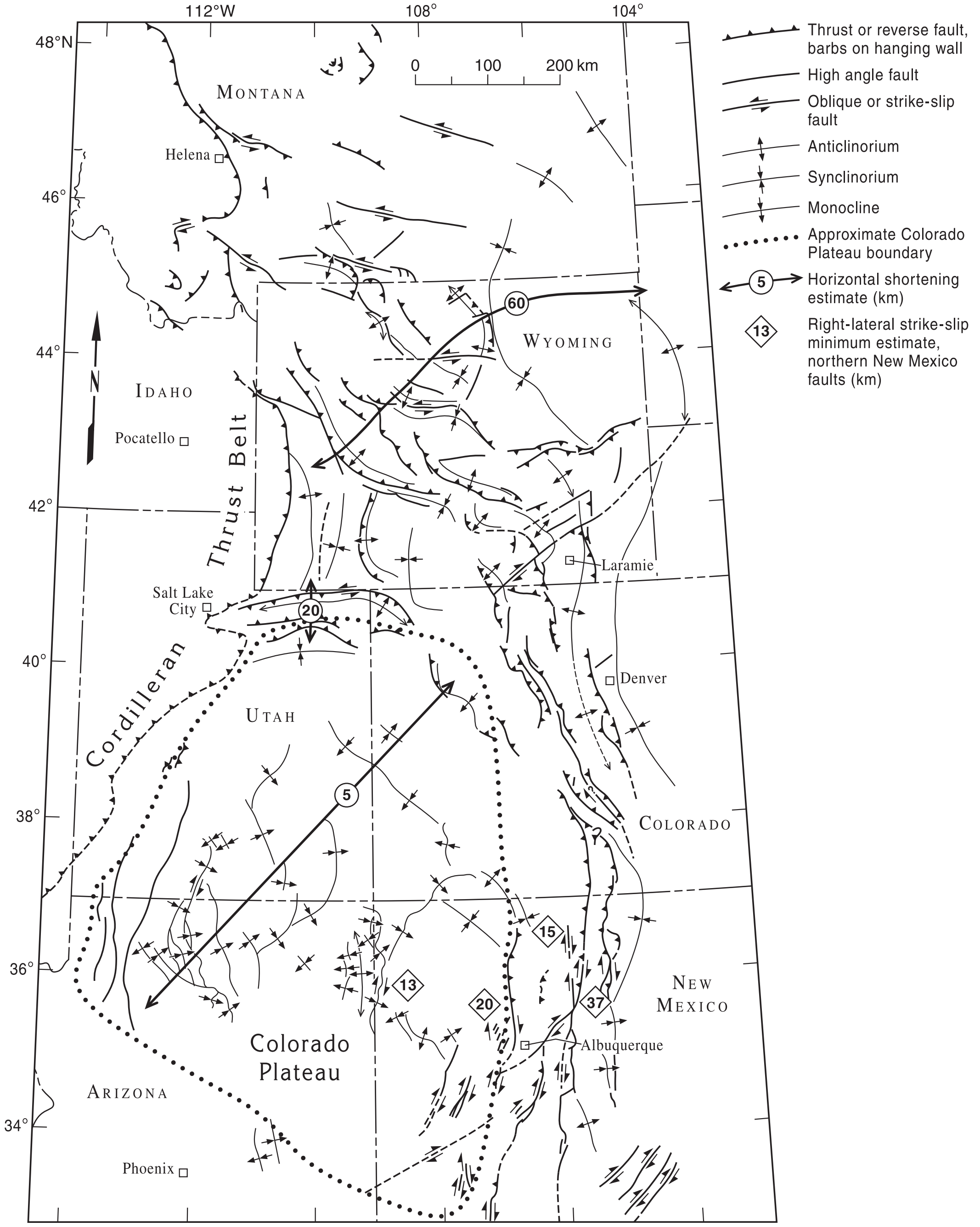

Figure 11. Regional tectonic map of the Colorado Plateau–Rocky Mountain area showing Laramide structures for the Colorado Plateau and central Rocky Mountains, shortening estimates, and minimum dextral-slip estimates for the southern Rocky Mountain area in northern New Mexico. Modified from Stone (1993a), Huntoon (1993), and Woodward (1984).

data of Stone (1993a), it is possible to construct a three-part transect that allows estimation of the net shortening from the southwestern Colorado Plateau to the Black Hills (Fig. 11). The three-part transect depicted in Figure 11 is subparallel to the regional shortening directions on the Colorado Plateau (Kelley, 1955) and in the central Rocky Mountains (Erslev, 1993). Shortening across monoclines in the Grand Canyon area of the Colorado Plateau was estimated by Huntoon (1993) to be <1%, which gives about 5 km of total shortening measured in the southern part of the transect in a northeast direction across the Colorado Plateau. The central part of the transect encompasses the Uinta uplift, shortening across which has been estimated as about 20 km (Bruhn et al., 1983; Stone, 1993b). The northern part of the transect is adopted from Stone (1993a) and encompasses about 60 km of shortening. The total shortening measured from the Grand Canyon area of the southwestern Colorado Plateau to the Black Hills of South Dakota thus is ~85 km.

The southern Rocky Mountains that bound the Colorado Plateau on the east are characterized by Laramide crustal shortening and dextral transpression, although a local area of dextral transtension is present near Albuquerque (Slack and Campbell, 1976; Cather, 1992). Estimation of net Laramide shortening in the southern Rocky Mountains is greatly complicated in most areas due to effects of subsequent rifting. The east-west component of Laramide shortening in central Colorado is ~30 km (Chase et al., 1992); east-west shortening in central and northern New Mexico was probably significantly less due to the southward decrease in crustal shortening in the southern Rocky Mountains (Chapin and Cather, 1981, p. 192). Mesozoic stratigraphic data require at least 33 km and allow as much as 110 km of regional dextral offset across the Laramide deformed zone in central and northern New Mexico. Although the magnitude of offset is unknown for many Laramide dextral-oblique faults, summation of known dextral offsets across four Laramide structures in northern New Mexico near the latitude of Santa Fe yields net offsets that are compatible with regional Mesozoic stratigraphic constraints. These four dextral-oblique structures (Fig. 11) are the Defiance monocline (13 km of dextral offset), the Sand Hill–Nacimiento fault system (minimum 20 km), the Tusas-Picuris fault (minimum 15 km), and the Picuris-Pecos fault (minimum 37 km), producing a net minimum dextral offset of about 85 km. Although this figure does not account for additional Laramide dextral slip of unknown magnitude along the oblique-slip frontal faults of the Sangre de Cristo uplift (Baltz and O'Neill, 1984; O'Neill, 1990), it significantly exceeds any plausible estimate of east-west shortening at this latitude and thus suggests that strike-slip components exceed dip-slip components within the Laramide dextral-oblique zone of northern New Mexico. The approximate equivalence between shortening in the central Rocky Mountain–Colorado Plateau area (~85 km) and dextral components of slip in the southern Rocky Mountains in northern New Mexico (minimum 85 km) has important implications for the Eulerian parameters of Colorado Plateau rotation.

Figure 12 summarizes three previously published Euler pole locations for Laramide rotation of the Colorado Plateau relative to cratonic North America (Hamilton, 1981, 1988; Chapin and Cather, 1981). In each case, I have used the aforementioned 85 km net shortening estimate in the Colorado Plateau–central Rocky Mountain area to calculate the magnitude of plateau rotation about these poles. Shortening estimates by the original authors were poorly constrained. Hamilton (1981, 1988) calculated shortening in the Wyoming area by assuming that about half the width of each Laramide basement uplift represents crustal shortening. Chapin and Cather (1981) estimated shortening north of the Colorado Plateau based on sparsely distributed petroleum-well penetrations of fold-thrust overhangs in the Wyoming region (Gries, 1981).

Hamilton (1981, 1988) has variously depicted the Euler pole for Laramide Colorado Plateau rotation to be in central New Mexico (Fig. 12A) or in the panhandle of Texas (Fig. 12B). The New Mexico Euler pole location requires ~6° of clockwise rotation to explain the observed 85 km shortening (Fig. 12A), whereas the Texas Euler pole position requires ~4.5° of clockwise rotation (Fig. 12B). Both of Hamilton's models predict significantly less dextral slip in northern New Mexico than appears to be present. Furthermore, both of these models predict crustal extension or transtension along the southeastern margin of the Colorado Plateau in southern New Mexico, which is contrary to the observed dominance of crustal shortening and dextral transpression in these areas (Harrison, 1989; Harrison and Chapin, 1990; Nelson, 1993; Seager et al., 1997). These geologic data suggest that the Euler pole for Laramide Colorado Plateau rotation was more remote and farther south than depicted by Hamilton (1981, 1988).

Chapin and Cather (1981, 1983) argued that the Colorado Plateau occupied a near-equatorial position relative to its pole of rotation (Fig. 12C). In this model, north-northeastward plateau rotation of <1° would account for the observed ~85 km shortening in the Colorado Plateau–central Rocky Mountain area. The linear displacement vectors associated with such an equatorial rotation, however, would not cause significant clockwise rotation of the Colorado Plateau. The Eulerian geometry of Chapin and Cather (1981) is compatible with the dominance of dextral transpression and crustal shortening observed along the eastern and southeastern Colorado Plateau boundary. It also predicts ~80 km of dextral offset in northern New Mexico, which is quite similar to the cumulative minimum 85 km of dextral offset estimated across the Defiance, Sand Hill–Nacimiento, Picuris-Pecos, and Tusas-Picuris structures. Although these structures are clearly in need of further study, it is unlikely that future work will produce the two-fold or (particularly) the four-fold reductions in estimates of net dextral slip that would be necessary, respectively, to accommodate the Laramide Euler pole locations of Hamilton (1981, 1988). Geological constraints are not sufficiently refined to rule out a moderately distant Euler pole approximately equidistant between those of Hamilton (1981) and Chapin and Cather (1981). Such a pole position, however, would allow no more than about 3° of clockwise Laramide plateau rotation.

Comparison of paleomagnetic poles for pre-Laramide (Mesozoic and upper Paleozoic) rocks on the Colorado Plateau with similar-age rocks on the craton have yielded a wide range of estimates of the amount of clockwise plateau rotation during Laramide and Neogene Rio Grande rift deformations. Estimates vary from as much as 10° to 15° (e.g., Steiner, 1988; Kent and Witte, 1993; Kent and Olsen, 1997) to <5° to 7° (Bryan and Gordon, 1990; Molina-Garza et al., 1995). Post-Laramide rotation of the Colorado Plateau related to opening of the Rio Grande rift was estimated by Hamilton (1981, 1988) to be about 3°. However, palinspastic restoration of rift-related extension documented by seismic reflection surveys in the San Luis basin (Kluth and Schaftenaar, 1994) and the Albuquerque basin (Russell and Snelson, 1994) allows only 1° to 1.5° of Neogene plateau rotation (Chapin and Cather, 1994). Geologic evidence thus suggests that the maximum magnitude of combined Laramide (3.0°) and Neogene (1.5°) plateau rotations is about 4.5°. The minimum plausible rotation is about 1°. These figures are consistent with the lower range of rotations indicated by paleomagnetic analysis and support other geologically inferred limits on plateau rotation (Chase et al., 1992).

CONCLUSIONS

1. Offsets of Mesozoic pinch-outs and facies transitions provide estimates of Laramide dextral displacements for the Defiance monocline (13 km; Kelley, 1967) and for the Sand Hill–Nacimiento fault system (20–33 km).

2. Mesozoic pinch-out data suggest that the approximate upper limit of allowable Laramide dextral offset across the Rio Grande rift is 40 km near Albuquerque and 60 km near Socorro.

3. Mesozoic stratigraphic constraints on net dextral offset across the entire Laramide deformed zone in northern and central New Mexico are imprecise, primarily because of broadly spaced control points and the widespread effects of Tertiary erosion. Minimum dextral displacement is 33 to 46 km; maximum dextral displacement is possibly 110 km.

4. Well-documented dextral displacements (net 52 km) of Proterozoic rocks and structures along the Tusas-Picuris and Picuris-Pecos faults in northern New Mexico probably represent minimum Laramide offsets because of the need to account for sinistral components related to other deformations.

5. Laramide shortening on and northward of the Colorado Plateau (~85 km) compares closely with known and suspected Laramide dextral slip in the southern Rocky Mountains of northern New Mexico (minimum 85 km), which argues against Euler pole locations near the Colorado Plateau.

6. Consideration of geological constraints for both Laramide deformation and Rio Grande rifting allows between about 1° and 4.5° of clockwise rotation of the Colorado Plateau during Late Cretaceous through Neogene time.

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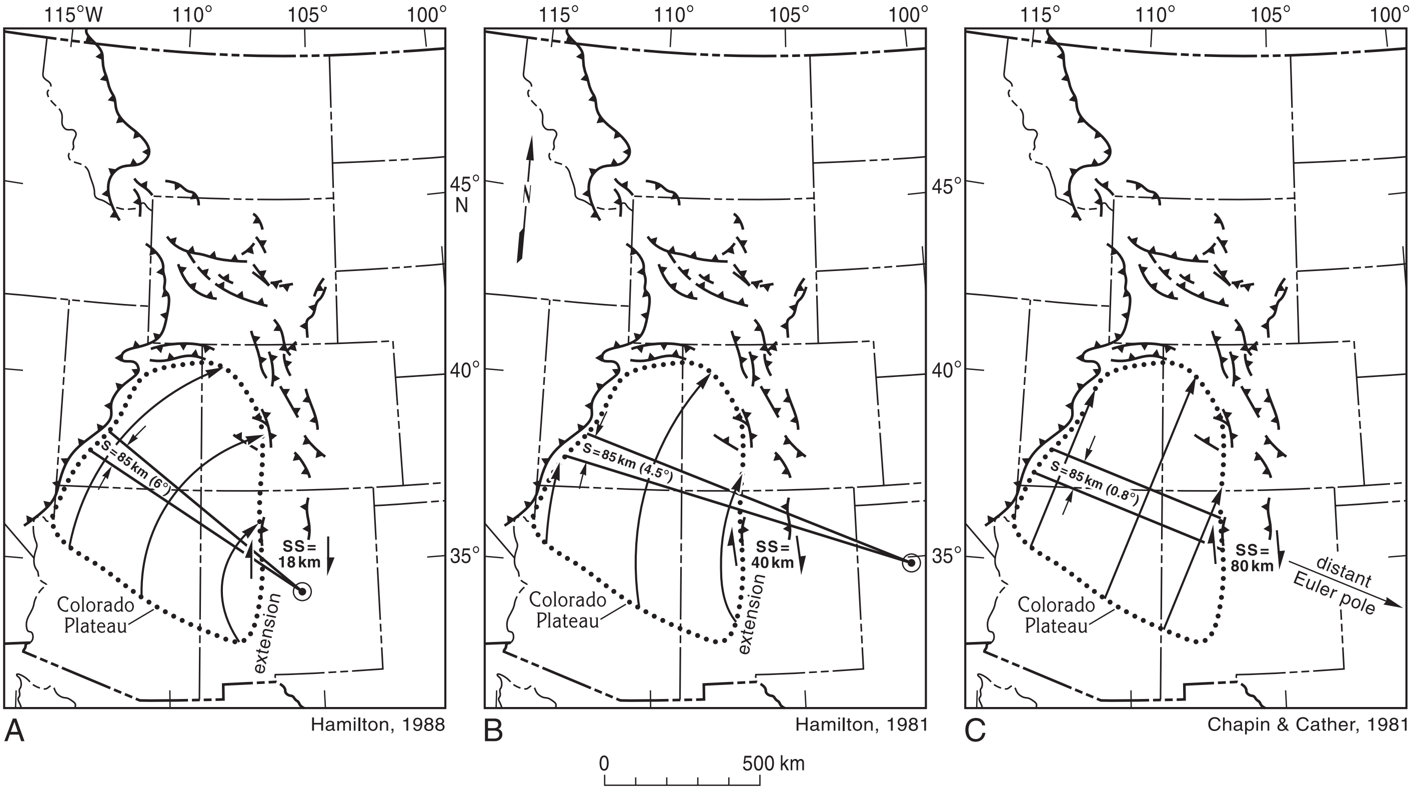

Figure 12. Maps showing published Euler pole models for rotation of the Colorado Plateau relative to cratonic North America during Laramide deformation. In each example, crustal shortening (S) within and north of the Colorado Plateau is assumed to be ~85 km (see text); the amount of strike slip in the southern Rocky Mountains (SS) and the rotation angle are calculated from this shortening value for each pole position. (A) Hamilton (1988); (B) Hamilton (1981); (C) Chapin and Cather (1981). Base map is from Hamilton (1988).

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