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LOWER PALEOZOIC ISOPACH MAPS OF SOUTHERN NEW MEXICO AND THEIR IMPLICATIONS FOR LARAMIDE AND ANCESTRAL ROCKY MOUNTAIN TECTONISM

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ABSTRACT.— New isopach maps for four lower Paleozoic sedimentary successions (Bliss Sandstone–El Paso Formation, Montoya Formation, Fusselman Dolomite, and Devonian strata) in southern New Mexico indicate the presence of pronounced dextral deflections in the isopach patterns for these strata, particularly in data-rich areas near their northern pinchouts. These deflections occur across faults of known or suspected Laramide and, in the east, Ancestral Rocky Mountain ancestry. The magnitude and interpreted origin of the best-defined of these dextral deflections are: Hot Springs fault system near Truth or Consequences (~26 km, mostly Laramide); Engle Basin (32–36 km, mostly Laramide; includes ~26 km value for Hot Springs fault system); Palomas Basin (57–60 km, ~26 km of which is attributable to Laramide slip on the Hot Springs fault system; the remainder is of unknown origin); and the Tularosa Basin (~40 km, largely tectonic in origin but the relative contributions of Laramide and Ancestral Rocky Mountain slip are unknown). Additional deflections may exist across the Pedernal Uplift but are in need of further study.

INTRODUCTION

Sedimentary isopach data, facies, and pinchout trends have proven useful in constraining the magnitude of lateral separations along both ancient (Budnik, 1986; Cather, 1999) and modern (Hill and Diblee, 1953) strike-slip fault systems. In southern New Mexico, southward-thickening, wedge-shaped units of Late Cambrian to Devonian age were deposited on the stable, northwest shelf of the Tobosa Basin (Galley, 1958; see review by Raatz, this guidebook). Thickness data for these geometrically simple, wedge-shaped units have the potential to provide useful piercing lines for analysis of lateral tectonic displacements during subsequent Ancestral Rocky Mountain, Laramide and Rio Grande rift deformations.

This report analyzes new isopach maps for four unconformity-bounded stratigraphic successions. These are the Bliss Sandstone and El Paso Formation (Upper Cambrian to Lower Ordovician), the Montoya Formation (Middle to Upper Ordovician), the Fusselman Dolomite (Lower to Middle Silurian), and Devonian strata. Early isopach maps of these units, such as those of Kottlowski (1963), employed relatively few control points that, when contoured, yielded relatively smooth isopach lines. Isopach maps of subsequent workers (e.g., Hayes and Cone, 1975; Foster, 1978) utilized a greater density of control points, particularly near the northern pinchouts of the units. Their maps locally exhibit pronounced dextral steps in the isopach patterns near the northern pinchouts, although these steps were contoured smoothly, and no attempt was made to analyze their origin.

Previous isopach maps of early Paleozoic units in southern New Mexico exhibit regionally continuous contours, despite crossing numerous major structural trends of various ages. We suggest that the true thickness pattern of these units (as opposed to the contoured pattern, which is interpretive) is undoubtedly at least somewhat discontinuous between structural blocks, given the 0.5 Ga period that has elapsed since the earliest of these units were deposited. Also, this period was punctuated by three major tectonic events (Ancestral Rocky Mountain, Laramide, and Rio Grande rift), all of which show evidence of oblique deformation. We further suggest that the lack of recognition of such lateral thickness discontinuities is the result of two effects: (1) widely separated control points on older isopach maps (this remains a problem in the southern part of the study area); and (2) utilization of a contouring method that is incapable of detecting strike-slip faults because contours are constructed to bend across faults instead of being allowed to terminate against them. It is important to note that only one class of faults, those that are post-depositional and purely dip-slip, produce no discontinuities in isopach lines. All others (growth faults, strike-slip faults, and oblique-slip faults) require that isopach lines terminate at faults. While it might be argued that the drawing of continuous contours across fault-bounded blocks is sufficiently accurate for the purposes of regional stratigraphic studies, it is a method insufficiently sensitive to be useful for piercing-line analysis.

The control points utilized in this report are the most numerous yet compiled for early Paleozoic units in southern New Mexico, and are compiled entirely from thickness data established by other workers. We constructed isopach maps by contouring structural blocks individually (Fig. 1). By this method, contouring mismatches between adjacent blocks become apparent. Discontinuities may then be analyzed to determine whether apparent lateral separation (i.e., deflection, *sensu* Cather, 1999) of contours is of structural or stratigraphic origin. Our maps also depict three reliability grades of isopach contours. Well-constrained contours, shown as solid lines, are those where both the *location* and *trend* are relatively well specified by two or more adjacent control points on a given structural block. Moderately constrained contours have insufficiently defined trends and are drawn as dashed lines. Poorly defined contours are those in which both *trend* and *location* are not uniquely determined, and are dashed and queried. For the purpose of map construction, the trends of poorly and moderately defined contours are drawn to be subparallel to nearby well-defined contours inasmuch as is allowed by adjacent control points. For the purposes of our piercing-line analysis, however, we emphasize the implications of the well-constrained contours, as the non-unique trends of the lesser-grade contours cannot be interpreted unambiguously.

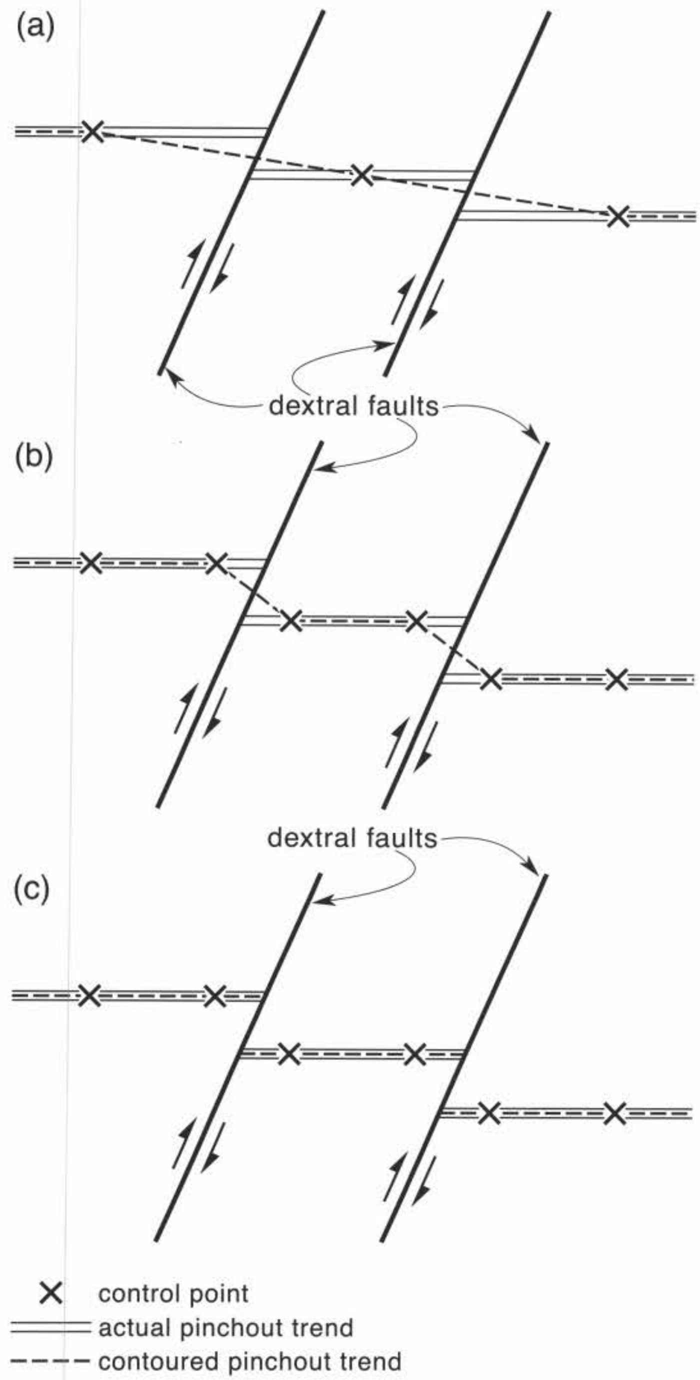


FIGURE 1. Schematic map showing importance of control-point density and contouring method in determining strike-slip offset of a stratigraphic piercing line (here shown as a pinchout). A, Smooth contouring of isolated, widely spaced control points fails to detect strike-slip offsets. B, The presence of multiple control points on each structural block allows delineation of the true pinchout trend except in areas where contour crosses bounding faults. C, Contouring method utilized in this report. Well-constrained contours are delineated using multiple points, and each structural block is treated as an individual contouring domain. Mismatches of well-constrained contours between adjacent blocks are then analyzed to determine if apparent lateral separation (i.e., deflection) is of structural or stratigraphic origin.

STRUCTURAL FRAMEWORK

Figure 2 shows the generalized Laramide structural framework for New Mexico. Note that many of the structures depicted in southeastern New Mexico are principally late Paleozoic structures that were reactivated during the Laramide orogeny. In central and northern New Mexico, Laramide structures are relatively well exposed, except those that may be buried beneath basins of the Rio Grande rift. In southern New Mexico, our understanding of the Laramide structural framework is more tenuous because of several factors: (1) late Tertiary cover is more widespread due to the Basin–Range faulting in southwestern New Mexico and the southward broadening of the Rio Grande rift; (2) extensive cover by the Datil–Mogollon and Sierra Blanca volcanic fields; and (3) relative scarcity of Laramide syntectonic deposits makes differentiation of Laramide structures from those of older or younger deformations more difficult.

Laramide structures in southern New Mexico have two dominant trends. West- to northwest-trending structures are the most widely recognized Laramide trend. These include several sinistral reverse faults in southwestern New Mexico (Seager and Mack, 1986; Lawton, 2000), the Bear Peak and southern Caballo thrust faults (Seager and Mack, 1986; Seager et al., 1997; Seager and Mack, in press), the Chavez Canyon reverse fault (Seager and Mayer, 1988), the Putnam overturned anticline (Seager et al., 1997; Seager and Mack, in press), the McGregor thrust fault (U.S. Army, 1998), and the Huapache monocline (Kelley, 1971). This latter structure is dominantly an Ancestral Rocky Mountain-structure, but also folds to a lesser extent strata as young as the Permian Grayburg Formation which indicates a younger, probably Laramide, phase of reactivation.

Another common orientation of Laramide structures in southern New Mexico is north to northeast (Fig. 2). Several of these structures are the southward continuation of Laramide dextral-oblique trends in central and northern New Mexico (e.g., Cather, 1999). North- to northeast-trending Laramide structures in southern New Mexico include the dextral Santa Rita–Hanover axis (Jones et al., 1967; Aldrich, 1972, 1976; Harrison, 1989, 1994), the dextral Chloride fault system (Harrison, 1989), the dextral Winston fault (Harrison, 1994), the dextral (locally dextral reverse) Hot Springs fault system (Harrison and Chapin, 1990; Harrison and Cather, in press; see Kucks et al., 2001, for the aeromagnetic expression of this regional fault system); north-trending folds and thrust faults in the Fra Cristobal Mountains (Nelson, 1993); north-trending folds in the northern Caballo Mountains (Kelley and Silver, 1952); the dextral Chupadera fault (Kelley and Thompson, 1964; Cather, 1999), the faulted and folded Mescalero anticlinorium (or arch; Kelley, 1971; this anticlinorium locally coincides with the western boundary of the late Mississippian–early Wolfcampian Pedernal uplift), the synclinal axis of the Sierra Blanca Basin (Kelley, 1971; Cather, 1991, this guidebook), and the dextral Pecos Slope buckles (Kelley, 1971). The Duncan–Tinnie anticlinorium (Kelley, 1971) is the axial structure of the south part of the late Paleozoic Pedernal Uplift, during which time it may have been a dextral structure (Ahlen, 1998). Reactivation of the Duncan–Tinnie anticlinorium during the Laramide, however, is suggested by numerous lesser

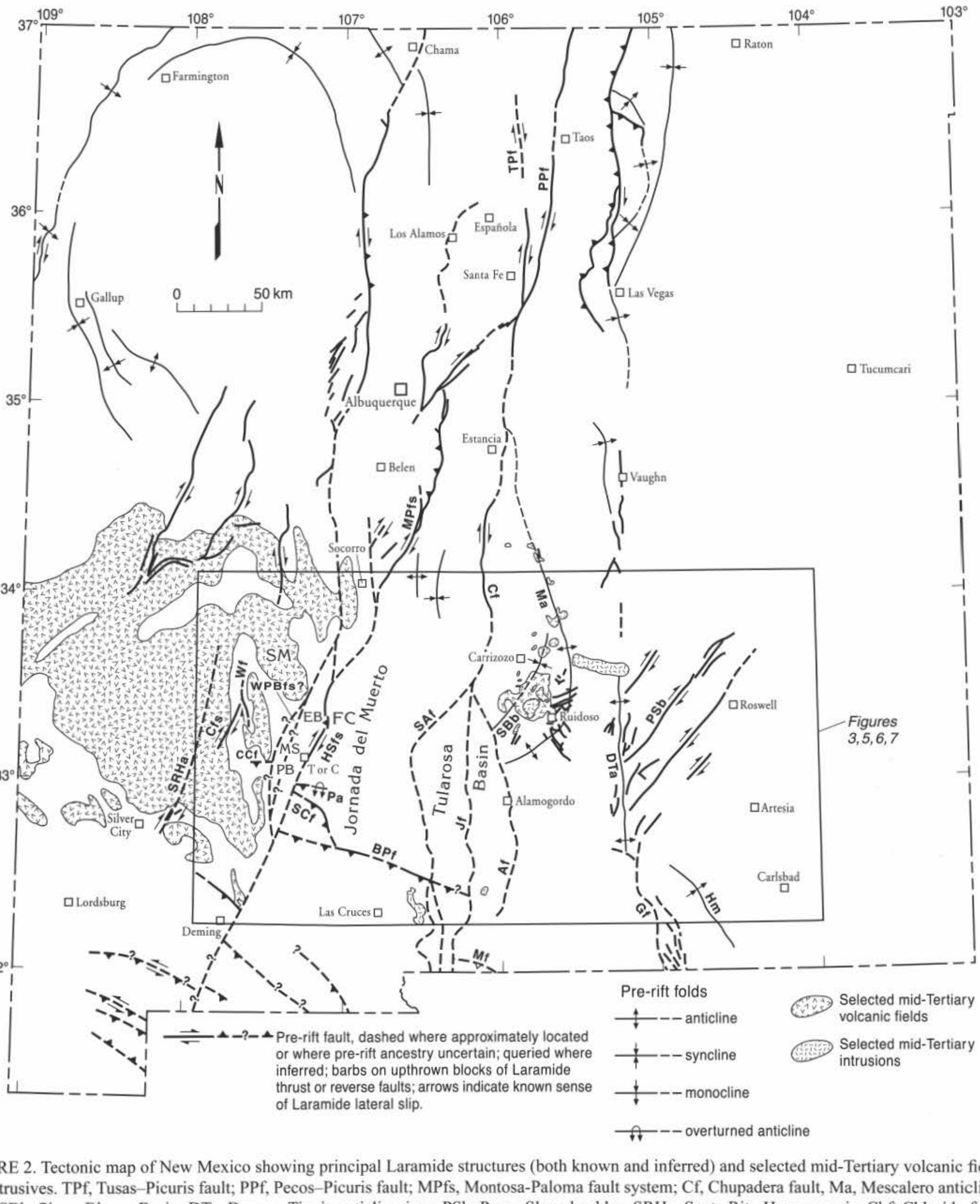


FIGURE 2. Tectonic map of New Mexico showing principal Laramide structures (both known and inferred) and selected mid-Tertiary volcanic fields and intrusives. TPf, Tusas–Picuris fault; PPf, Pecos–Picuris fault; MPfs, Montosa-Paloma fault system; Cf, Chupadera fault, Ma, Mescalero anticlinorium; SBb, Sierra Blanca Basin; DTa, Duncan-Tinnie anticlinorium; PSb, Pecos Slope buckles, SRHa, Santa Rita-Hanover axis; Chf, Chloride fault; Wf, Winston fault, CCf, Chavez Canyon fault; WPBfs?, western Palomas Basin fault system (hypothetical Laramide faults beneath western Palomas and Engle Basins); HSfs, Hot Springs fault system; Pa, Putnam anticline; BPf, Bear Peak fault; SAf, San Andres fault; Jf, Jarilla fault; Af, Alamogordo fault; Gf, Guadalupe fault; Hm, Huapache monocline; Mf, McGregor fault; SM, San Mateo Mountains; EB, Engle Basin; FC, Fra Cristobal Mountains; MS, Mud Springs Mountains; PB, Palomas Basin. Note some Laramide structures in south-central and southeastern New Mexico, particularly the Duncan-Tinnie anticlinorium and the Huapache monocline, are reactivated Ancestral Rocky Mountain structures.

faults and folds that involve rocks as young as the Yeso and San Andres Formations (e.g., Bowsher, 1991; Yuras, 1991). Numerous north–northwest to north–northeast folds, interpreted to be Laramide in age by Black (1975, 1976), fold strata of the Permian Yeso and San Andres formations on the Otero platform.

Other north-trending structures in southern New Mexico depicted in Figure 2 are less well constrained. Both the Chupadera fault, which has a Laramide component to its history (Cather, 1999, table 1), and the Mescalero anticlinorium, which may have both Laramide and Ancestral Rocky Mountain histories, enter the northern part of the Neogene Tularosa rift basin. To the north, these structures appear to connect through the Estancia Basin with the Picuris–Pecos fault, a well-documented structure that exhibits 37 km of dextral separation of Proterozoic structures and lithologies (Miller et al., 1963; Karlstrom and Daniel, 1993; Daniel et al., 1995). The timing of dextral slip on the Picuris–Pecos fault, however, is controversial (see below). Whatever the age of dextral slip, we suggest that such slip may be manifested southward along trend, in the Tularosa Basin region. Although the nature and distribution of Laramide and Ancestral Rocky Mountain faults in the Tularosa Basin are essentially unknown, we make the simplifying assumption that the major Neogene faults that bound and transect the Tularosa Basin (the San Andres, Jarilla, and Alamogordo faults) are the most likely structures to have had a pre-rift history. We note, however, that because of the scarcity of subsurface data on the White Sands Missile Range, other fault geometries are possible, particularly in the deep, essentially unexplored, western part of the Tularosa Basin. We also invoke hypothetical faults beneath the Palomas and Engle rift basins (the western Palomas Basin fault system) to have a possible pre-rift histories. This fault system corresponds locally to exposed faults and steep gravity gradients (Keller and Cordell, 1983) in the western part of the Palomas Basin, and a pre-rift history of dextral slip in this area is suggested by our analysis (below) of early Paleozoic isopach trends.

Because of the possibility of significant strike-slip of Laramide and/or late Paleozoic age on the regionally extensive, northerly-trending structures of southern New Mexico, we utilize these structures to define structural blocks. To test the possibility of lateral slip on these bounding structures, we contour the thickness-control points for early Paleozoic units on each block individually, and then analyze any mismatches between adjacent blocks. This avoids the implicit, *a priori* assumption of no strike-slip that is inherent in contouring methods employed by earlier workers.

LOWER PALEOZOIC ISOPACH MAPS

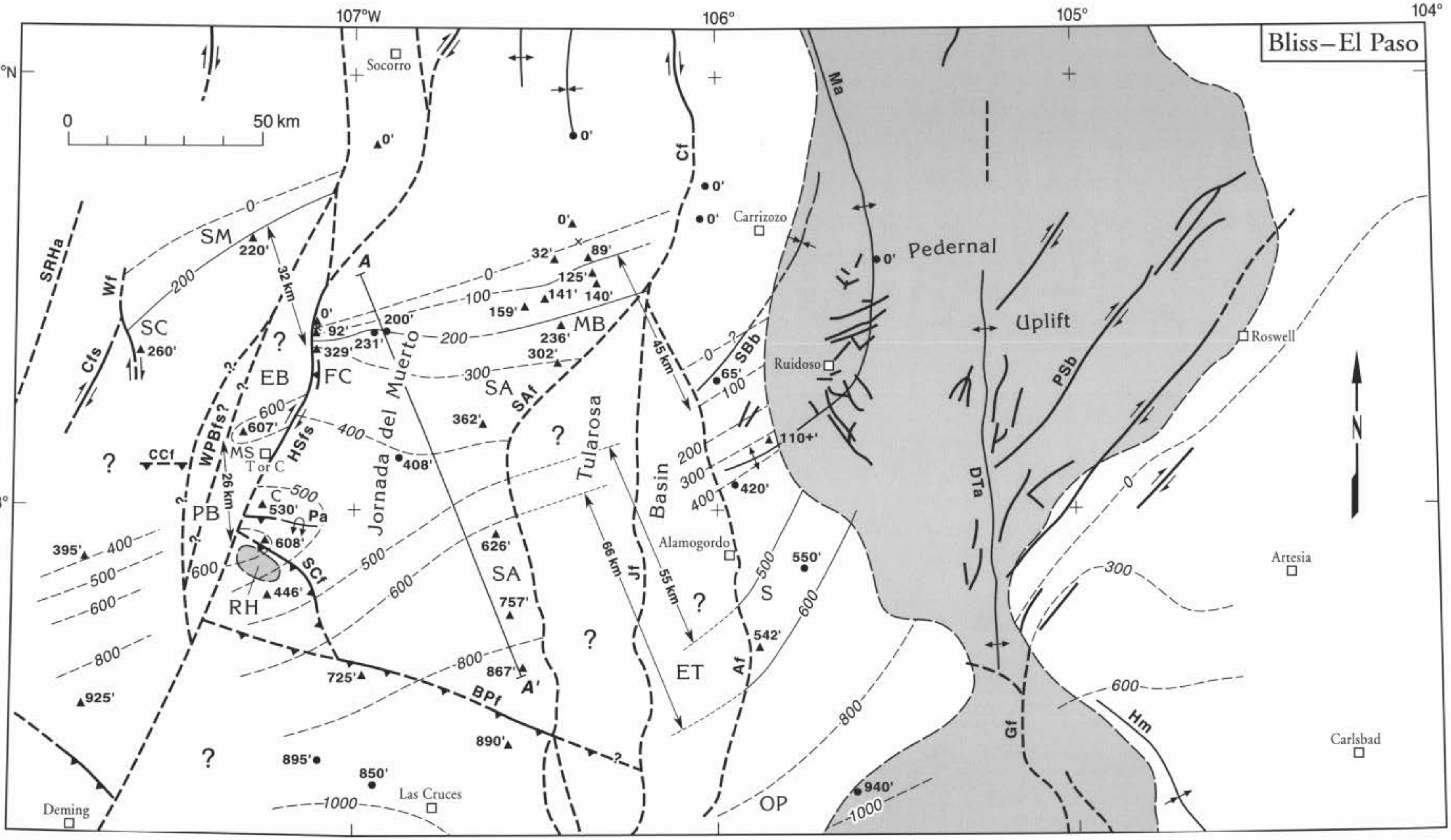
The lithology, age, and nomenclatural intricacies of lower Paleozoic strata in southern New Mexico have been thoroughly described in the literature (e.g., Kottlowski, 1963; Foster, 1978; Hayes and Cone, 1975; King and Harder, 1985; Clemons, 1991; Mack et al., 1998) and will not be further elaborated upon here. For the purposes of map construction, we utilize four isopach intervals. These are Bliss Sandstone–El Paso Formation, the Montoya Formation, the Fusselman Dolomite, and Devonian strata. Each isopach interval is an unconformity-bounded, southward thickening sedimentary succession that was deposited on the stable, northwest shelf of the Tobosa Basin (Raatz, this guidebook).

Bliss Sandstone and El Paso Formation

The Bliss Sandstone and El Paso Formation are a succession of sandstone, limestone and dolomite of Late Cambrian to Early Ordovician age that represent the Sauk sequence in southern New Mexico (Sloss, 1988, fig. 1). East of the Pedernal Uplift (Fig. 3), the zero isopach of the combined Bliss–El Paso trends southwest from the southern panhandle of Texas to where it intersects the late Paleozoic Pedernal Uplift near the latitude of Artesia (Hayes and Cone, 1975; Greenwood et al., 1977; Frenzel et al., 1988). On trend to the southwest, this zero isopach projects across the Pedernal Uplift toward ~900 ft thicknesses in the Otero Platform area. On the Sacramento–Otero Platform block, east of the Alamogordo fault, the zero isopach is imprecisely constrained to be near the latitude of Ruidoso. It is thus dextrally deflected (*sensu* Cather, 1999, p. 852) relative to the same isopach to the east of the Pedernal Uplift. The only well-defined contour *trends* on the Sacramento–Otero Platform block are the 500 ft and 600 ft isopachs. They project southwestward across the Tularosa Basin toward ~900 ft thicknesses in the southern San Andres Mountains, well to the south of the 500 ft and 600 ft isopachs in the central San Andres Mountains.

On the Jornada del Muerto block, the best-defined isopachs (i.e., trend and location are both constrained) occur near the northern pinchout. There, the 200 ft isopach is perhaps the best defined. West of the Fra Cristobal Mountains, this contour must deflect sharply at least 32 km to the north to accommodate the 220 ft thickness of Bliss–El Paso in the San Mateo Mountains (Kelley and Furlow, 1965; Foster, 1978). Control points in the San Mateo

FIGURE 3. Isopach map of combined Bliss Sandstone and El Paso Formation, and equivalent units. Contour domains for this and subsequent maps are defined by north–northeast-striking pre-rift faults (Fig. 2). Contours for which trend and orientation are relatively well defined are shown as solid lines and are emphasized in our analysis. Pedernal Uplift of late Paleozoic age is defined by the Pennsylvanian zero isopach of Meyer (1966, fig. 48). Control points west of Pedernal Uplift are from Foster (1978), Kottlowski (1963), R. H. Broadhead (2002, written commun.), Kelley and Furlow (1965), and Bauer and Lozinski (1991). Pinchout exposures are from McCleary (1960) and Bachman (1968). Contour lines east of the Pedernal Uplift are from Greenwood et al. (1977) and Hayes and Cone (1975). Contour interval is variable. A-A' is line of section for Figure 4. Structures are: SRHa, Santa Rita–Hanover axis; Chf, Chloride fault; Wf, Winston fault; CCf, Chavez Canyon fault; WPBfs?, hypothetical west Palomas Basin fault system; HSfs, Hot Springs fault system; Pa, Putnam anticline; SCf, southern Caballo fault; BPf, Bear Peak fault; SAf, San Andres fault; Cf, Chupadera fault; Jf, Jarilla fault; Af, Alamogordo fault; Ma, Mescalero anticlinorium; SBb, Sierra Blanca Basin; DTa, Duncan–Tinnie anticlinorium; PSb, Pecos Slope buckles; Hm, Huapache monocline; Gf, Guadalupe fault. Localities are: SM, San Mateo Mountains; SC, Sierra Cuchillo; EB, Engle Basin; PB, Palomas Basin; MS, Mud Springs Mountains; RH, Red Hills; FC, Fra Cristobal Mountains; C, Caballo Mountains; SA, San Andres Mountains; MB, Mockingbird Gap; ET, eastern Tularosa Basin; S, Sacramento Mountains; OP, Otero Platform.



Pre-rift fault, dashed where approximately located or where pre-rift ancestry uncertain; queried where inferred; barbs on upthrown blocks of Laramide thrust or reverse faults; arrows indicate known sense of Laramide lateral slip.

Pre-rift folds

- anticline
- syncline
- monocline
- overturned anticline

Late Paleozoic uplifts of Ancestral Rocky Mountains. Pedernal uplift delineated by zero isopach of Pennsylvanian rocks (Meyer, 1966, fig. 48). Red Hills (RH) area of mild uplift shown where Pennsylvanian strata locally overlie El Paso Formation (Seager and Mack [in press]).

Control Points

▲ outcrop ● well × exposure of pinchout

100 — — ?– Isopach contour (feet); solid where trend and location are well constrained; dashed where trend uncertain; queried where trend and location uncertain.

← 40 km → Deflection estimate using best-defined isopach contours

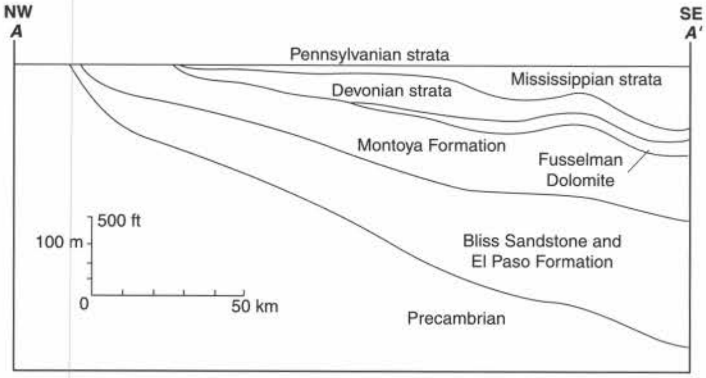


FIGURE 4. North–northwest cross section of lower Paleozoic strata on the Jornada del Muerto block. Datum is base of Pennsylvanian. Vertical exaggeration is ~165x.

Mountains and Sierra Cuchillo establish a northeast trend for the 200 ft contour in this area; this is virtually the only well-defined isopach trend for lower Paleozoic strata in the westernmost part of the study area. The northeast trend of the 200 ft contour is compatible with regional east–northeast trends of near-zero isopachs in regions west of the study area (Hayes and Cone, 1975, fig. 4).

The Hot Springs fault system juxtaposes ~400 ft thicknesses to the east with ~600 ft thicknesses in the Mud Springs Mountains. Thicknesses equivalent to those in the Mud Springs Mountains occur in the southern Caballo Mountains, across the Hot Springs fault system ~26 km to the south.

The Bliss–El Paso thins to the north–northwest in a fairly systematic fashion, complicated only locally by looping isopachs. The dominance of relatively linear isopachs in the Bliss–El Paso allows for relatively confident interpretation of deflections between structural blocks. Most of the taper of the Bliss–El Paso is related to decreased sedimentary accommodation to the north during deposition and to beveling by pre-Montoya erosion (Fig. 4). The northernmost limit of the units, however, is determined by pre-Pennsylvanian beveling (Fig. 4).

The near-zero contours on the Bliss–El Paso isopach map of Hayes and Cone (1975, fig. 4) show a step-wise pattern that is in many ways similar to that in our Figure 3. Rather than depicting discontinuous isopach lines, however, Hayes and Cone connected their data points with continuous isopach lines of northwest or north–northwest trend. While such correlations cannot be ruled out, we note that no such trends are defined elsewhere on the Bliss–El Paso isopach map (Fig. 3). We also note that the northwest-trending zero isopach that Hayes and Cone (1975) portrayed as connecting between the zero isopach east of the Pedernal Uplift and that near Mockingbird Gap crosses the Sacramento–Otero Platform block near Alamogordo. By our analysis, however, the only well-defined isopach trends (500 ft and 600 ft contours) on this structural block are northeast, orthogonal to those of Hayes and Cone (1975).

Woodward et al. (1997a, fig. 3) cited the early isopach maps for the Bliss Sandstone by Kottlowski (1963) as an argument against major Laramide dextral slip in southern New Mexico, and noted that the continuity of an east–west band of oolitic hematite facies that passes south of Truth or Consequences also prohibits such slip. (Interestingly, in a later paper, Woodward et al. (1999) argued for 125 km of Ancestral Rocky Mountains dextral offset on north-striking faults in central New Mexico, despite their earlier statements that lower Paleozoic patterns prohibit such subsequent offsets.) As pointed out to us by F. E. Kottlowski (1998, oral communication), however, several factors contribute to the obsolescence of his 1963 maps, now nearly 40 years old. These include: (1) the addition of new thickness data, particularly in the southern San Mateo Mountains (Furlow, 1965; Hayes and Cone, 1975; Foster, 1978), that require pronounced dextral steps for the near-zero isopach lines, and (2) a greater appreciation of the complexity of distribution of hematitic oolites in the Bliss. The oolitic facies depicted by Kottlowski (1963, fig. 3) was derived from the earlier work of Kelley (1951). The distribution of oolitic hematite in the Bliss has been shown by subsequent workers to be much more widespread than envisioned by Kelley (1951), who did not recognize oolite occurrences in the Fra Cristobal Mountains (McCleary, 1960), San Mateo Mountains (Furlow, 1965), and in the Mud Springs Mountains (Hill, 1956; Maxwell and Oatman, 1990). Indeed, in the western part of the study area, the greatest concentration of hematitic oolites occurs in the San Mateo Mountains (Hayes and Cone, 1975, fig. 14), an area which, at the time of Kelley's (1951) compilation, was not even known to contain lower Paleozoic rocks.

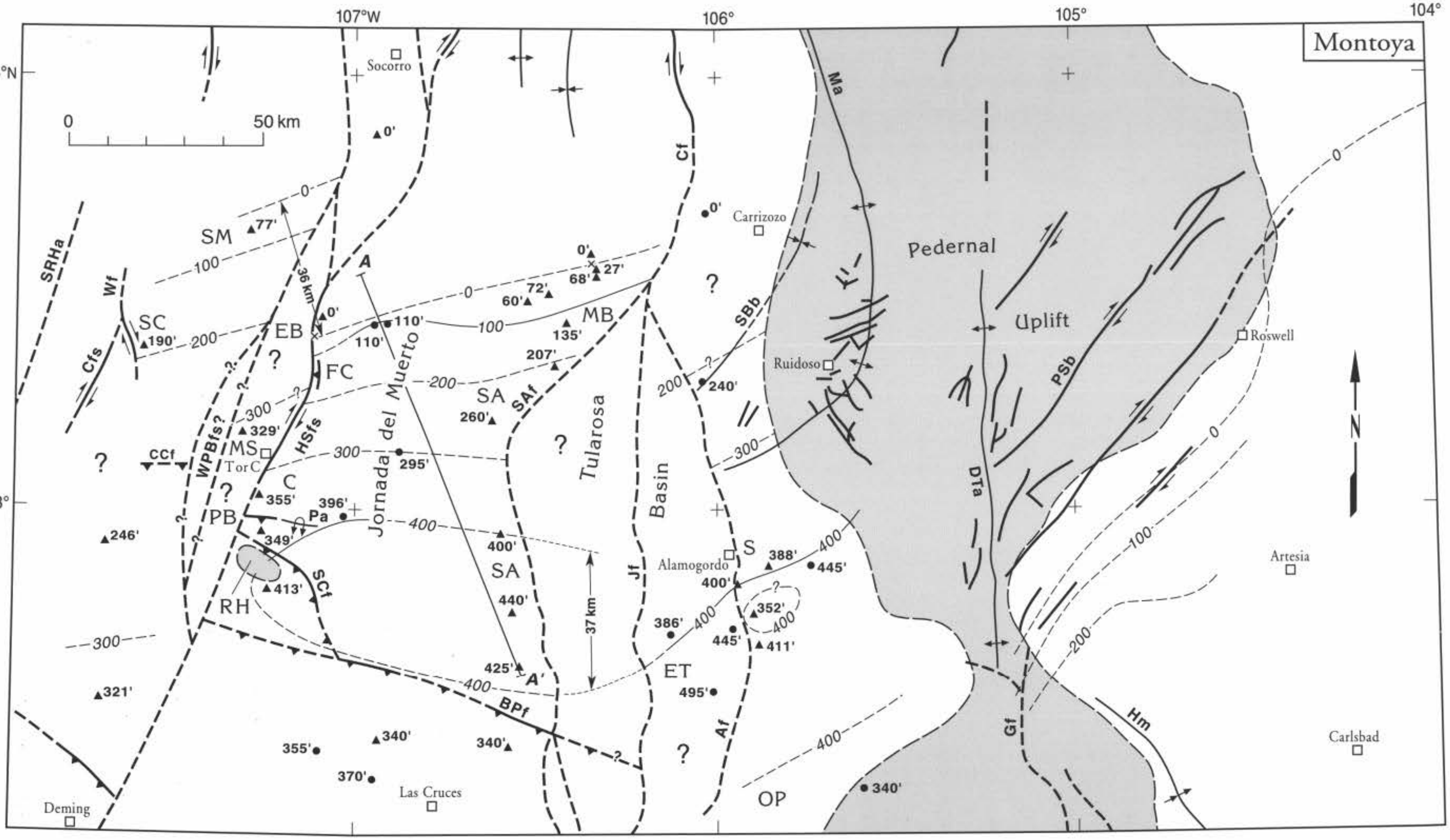
Substantial dextral deflections of Bliss–El Paso isopachs exist across the Tularosa Basin (45 km, 55 km, 66 km), across the Hot Springs fault system (~26 km), and across the Engle Basin (~32 km). Additional dextral deflections also may occur across the Pedernal Uplift (see below).

Montoya Formation

Near the latitude of Alamogordo and northward, the Montoya Formation (or Group; Middle to Upper Ordovician) tapers to the north–northwest due to the effects of syndepositional thinning, pre-Silurian beveling and, near its northern limit, pre-Pennsylvanian erosion (Fig. 4). To the south, the Montoya displays irregular thickening and thinning in the 300–500 ft range (Fig. 5; Kottlowski, 1963, fig. 5; Hayes and Cone, 1975, fig. 29) over a broad region of sparse control characterized by looping, nonlinear isopach contours.

East of the Pedernal Uplift, the zero isopach line trends southwestward to where it intersects the Duncan–Tinnie anticlinorium somewhat south of the latitude of Artesia. Across the uplift, on the Sacramento–Otero Platform block, the zero isopach may step dextrally far to the north, to an imprecisely constrained location north of the latitude of Ruidoso. Several factors, however, complicate interpretations in this area (see below).

FIGURE 5. Isopach map of Montoya Formation. Control points for areas west of the Pedernal Uplift are from Kottlowski (1963), Foster (1978), Furlow and Kelley (1965), and R. H. Broadhead (2002, written commun.). Pinchout exposures from McCleary (1960) and Bachman (1968). Contours east of the Pedernal Uplift are from Hayes and Cone (1975) and Greenwood et al. (1977). Contour interval is variable. A-A' is line of section for Figure 4. Structures and localities are listed in caption of Figure 3.



▲ -?- ▲ Pre-rift fault, dashed where approximately located or where pre-rift ancestry uncertain; queried where inferred; barbs on upthrown blocks of Laramide thrust or reverse faults; arrows indicate known sense of Laramide lateral slip.

Pre-rift folds

- anticline
- syncline
- monocline
- overturned anticline

Late Paleozoic uplifts of Ancestral Rocky Mountains. Pedernal uplift delineated by zero isopach of Pennsylvanian rocks (Meyer, 1966, fig. 48). Red Hills (RH) area of mild uplift shown where Pennsylvanian strata locally overlie El Paso Formation (Seager and Mack [in press]).

Control Points

▲ outcrop ● well × exposure of pinchout

—100— – –?– Isopach contour (feet); solid where trend and location are well constrained; dashed where trend uncertain; queried where trend and location uncertain.

←40 km→ Deflection estimate using best-defined isopach contours

On the Sacramento–Otero Platform block, the only well-defined isopach is the northeast-trending 400 ft contour near Alamogordo. It projects southwestward into the eastern Tularosa Basin, where it appears to be on-trend with the 400 ft contour there. These relations suggest there is little or no post-early Paleozoic strike slip on the Alamogordo fault.

The 400 ft contour defined on the eastern Tularosa Basin block must deflect dextrally ~37 km to match with the analogous contour in the central San Andres Mountains. An area of thick Montoya is outlined by the looping 400 ft contour in the southern part of the Jornada del Muerto block. A similar thick area is present on the Sacramento–Otero Platform block, but it is dextrally off-trend across the western Tularosa Basin.

The zero and, particularly, the 100 ft isopachs are the best-defined Montoya contours on the Jornada del Muerto block. They project west–southwest toward the Engle basin, where they must deflect ~36 km to accommodate the Montoya section present in the San Mateo Mountains (Furlow, 1965; Foster, 1978, fig. 5). A significant dextral deflection of the 300 ft isopach may be required across the Hot Springs fault system, as shown by thickness contraints in the Mud Springs and Caballo Mountains. This deflection is less well defined, however, than the Fra Cristobal–San Mateo deflection due to the effects of widely spaced control points on the Jornada del Muerto block and the lack of local trend constraints on structural blocks west of the Hot Springs fault system. Regional contraints, however, suggest a continuation of west–southwest isopach trends in regions to the west of the study area (Hayes and Cone, 1975, fig. 29).

Fusselman Dolomite

The Fusselman Dolomite (Lower to Middle Silurian) in south-central New Mexico thins to the northwest in response to decreased syndepositional accommodation in that direction as well as the effects of pre-Devonian beveling (Fig. 4). This contrasts with the other lower Paleozoic units discussed in this report, whose ultimate northern limit is a result of pre-Pennsylvanian erosion.

East of the Pedernal Uplift, the zero isopach of the Fusselman Dolomite trends southwest and intersects the Pedernal Uplift south of the latitude of Artesia (Fig. 6). To the west, the zero isopach must deflect dextrally across the Pedernal Uplift to the vicinity of Alamogordo. On the Sacramento–Otero Platform block, only the trend of the 100 ft isopach is well defined. It projects southwestward toward the eastern Tularosa Basin, where similar thicknesses exist. These data argue, again, that there can be little post-early Paleozoic strike-slip on the Alamogordo fault. The zero isopach near Alamogordo, assuming that it trends southwest (subparallel to the 100 ft contour), must deflect dextrally ~40 km across the Tularosa Basin to where it is exposed in the central San Andres Mountains.

On the Jornada del Muerto block, the zero isopach continues on a southwest trend to where it is again exposed in the Caballo Mountains near Burbank Canyon (Seager and Mack, in press). The pinchout geometry is complicated by relations in the Red Hills area nearby to the south (Fig. 6). There, moderate uplift and erosion during Late Mississippian to Early Pennsylvanian caused Pennsylvanian strata to disconformably overlie the El Paso Formation, with ~300 m of section (including Fusselman) erosionally removed south of the southern Caballo fault (Seager and Mack, in press).

To the west of the Caballos Mountains, the zero pinchout must deflect dextrally ~57 km to accommodate control points in the Sierra Cuchillo that closely bracket the zero isopach. The nature of this deflection is poorly constrained, however, because of the lack of trend constraints west of the Hot Springs fault system. The Fusselman Dolomite is not present in the Mud Springs Mountains. Because the Mud Springs Mountains are dextrally 28 km off the Fusselman pinchout trend defined on the Jornada del Muerto block, this thus represents a *maximum* value for possible dextral separation due to strike-slip on the Hot Springs fault system.

In the eastern Tularosa Basin south of Alamogordo, the thickness of the Fusselman Dolomite in several wells was reported by King and Harder (1985) to be much greater than that reported for the same wells by Kottlowski (1963) and Foster (1978). The discrepancies seem to relate to the pick of the basal contact of the Fusselman Dolomite with the underlying dolomite of the Montoya Formation. With the help of R. F. Broadhead, we re-examined electric logs and sample logs for the wells in question. Our thickness interpretations are similar to those of Kottlowski (1963) and Foster (1978), and are utilized on Figure 6.

Devonian Strata

Devonian strata include the Percha Shale, Contadero Formation, Sly Gap Formation, and Oñate Formation that were deposited in Middle to Late Devonian time. These strata in south-central New Mexico thin to the northwest in a fairly systematic fashion, although looping contours and irregular thickness variations occur locally in areas south of the latitude of Alamogordo (Fig. 7). Most of the northwestward thinning of the Devonian strata is due to variations in syndepositional accommodation and to minor pre-Mississippian erosion; only the northernmost extent of the Devonian strata was subject to pre-Pennsylvanian erosion (Fig. 4).

East of the Pedernal Uplift, the zero isopach of Devonian strata trends southwest. It is dextrally deflected across the Pedernal to an imprecisely defined location on the Sacramento–Otero Platform block between the latitudes of Ruidoso and Carrizozo. Except for local segments of looping contours south of Alamogordo, there are no well-defined isopach trends on either the Sacramento–Otero Platform block or the eastern Tularosa Basin block. Because of the lack of systematic trend data on these blocks, deflection estimates based on Devonian strata across the western Tularosa Basin are ambiguous.

On the central and northern parts of the Jornada del Muerto block, isopach contours generally trend southwest (Fig. 7). The

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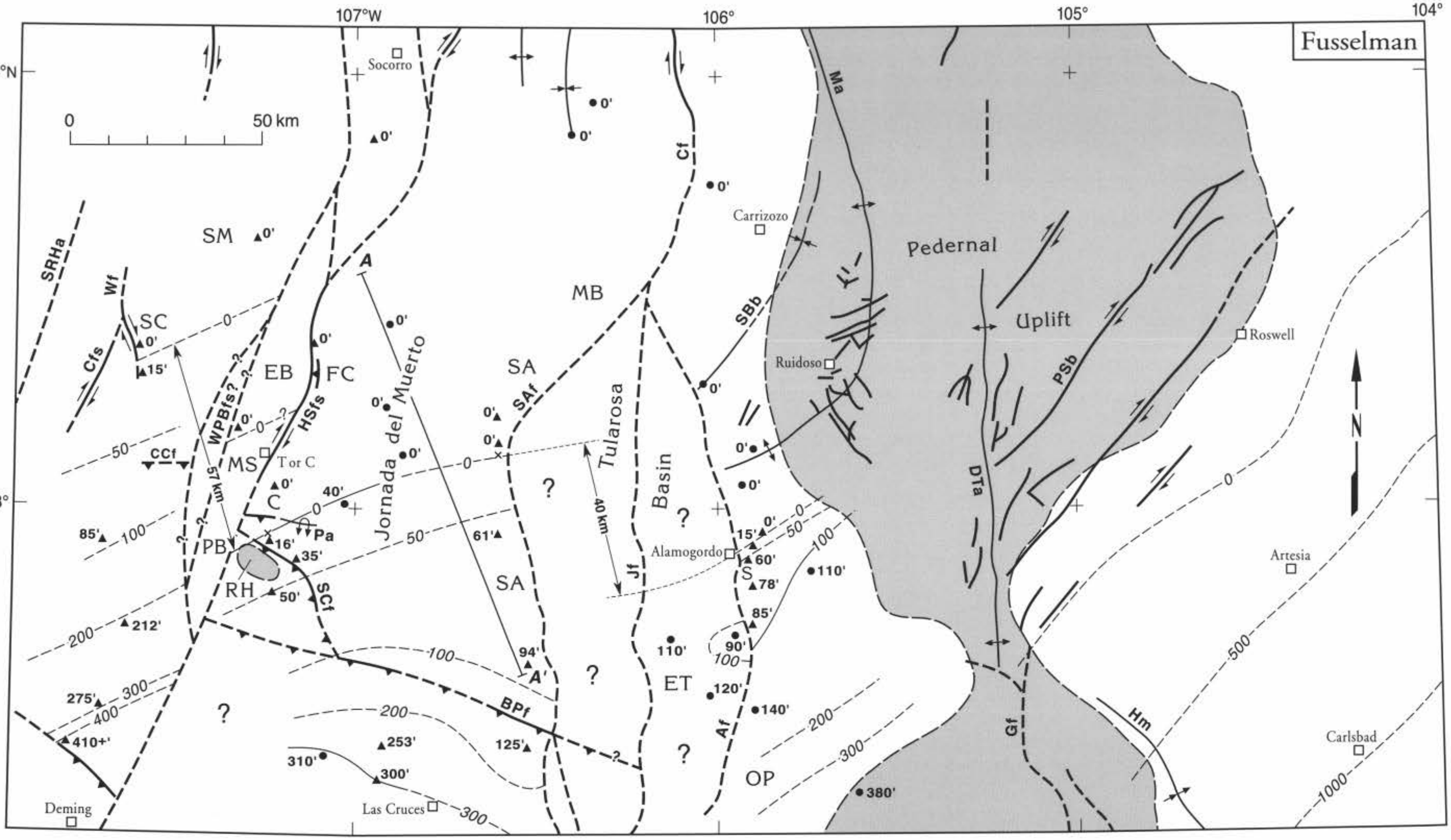
FIGURE 6. Isopach map of the Fusselman Dolomite. Control points west of the Pedernal Uplift are from Kottlowski (1963), and Foster (1978). Pinchout exposures are from Kottlowski et al. (1956) and Seager and Mack (in press). Contours east of Pedernal Uplift are from Greenwood et al. (1977). Contour interval is variable. A-A' is line of section for Figure 4. Structures and localities are listed in caption of Figure 3.



Pre-rift fault, dashed where approximately located or where pre-rift ancestry uncertain; queried where inferred; barbs on upthrown blocks of Laramide thrust or reverse faults; arrows indicate known sense of Laramide lateral slip.

Pre-rift folds
- anticline
- syncline
- monocline
- overturned anticline

Late Paleozoic uplifts of Ancestral Rocky Mountains. Pedernal uplift delineated by zero isopach of Pennsylvanian rocks (Meyer, 1966, fig. 48). Red Hills (RH) area of mild uplift shown where Pennsylvanian strata locally overlie El Paso Formation (Seager and Mack [in press]).

Control Points

▲ outcrop • well × exposure of pinchout

—100— – –?– Isopach contour (feet); solid where trend and location are well constrained; dashed where trend uncertain; queried where trend and location uncertain.

←40 km→ Deflection estimate using best-defined isopach contours

pinchout of Devonian strata is exposed near Burbank Canyon in the southern Caballo Mountains (Seager and Mack, in press). Nearby to the south across the Caballo fault, the pinchout trend is complicated by a local area of modest Late Mississippian to Early Pennsylvanian uplift in the Red Hills (Seager and Mack, in press). West of the Hot Springs fault system, the zero isopach must deflect dextrally from the southern Caballo Mountains a minimum of 26 km to accommodate the 105 ft thickness of Devonian strata in the Mud Springs Mountains. Additional dextral deflection, totaling ~60 km, must exist between the Caballo Mountains and the Sierra Cuchillo, where 65 ft of Devonian strata are present (Jahns, 1955). Evaluation of the origin of Devonian isopach deflections west of the Hot Springs fault system, however, are complicated by the lack of trend data in this area.

DISCUSSION

Pedernal Uplift

A major positive area in the Ancestral Rocky Mountains, the north-trending Pedernal Uplift divides the Delaware basin to the east from the Orogrande Basin to the west. In southern New Mexico, the axial structure of the Pedernal is the Duncan–Tinnie anticlinorium, an inadequately studied basement high upon which are located multiple generations of lesser folds and faults (Kelley, 1971; Bowsher, 1991). Most of the basement relief on the anticlinorium is late Paleozoic, but younger faults and folds, presumably Laramide in age, occur along the Duncan–Tinnie trend and involve strata as young as the Permian San Andres Formation. The Pecos Slope buckles, which were active as dextral structures during the Laramide (Kelley, 1971), coincide spatially with a major salient in the Pedernal Uplift near Roswell. This suggests that the buckles also may have been active in the late Paleozoic.

The Duncan–Tinnie anticlinorium was interpreted by Ahlen (1998) as a dextral oblique structure, although the reasons for this interpretation were not stated. To the north, the Duncan–Tinnie trend continues along strike through the Vaughn area (Fig. 2) to link with the eastern frontal structures of the Laramide Sangre de Cristo uplift (Kelley, 1972). These frontal structures had late Paleozoic precursors that have been interpreted by Baltz and Myers (1999) to be dextral oblique thrusts. The Central Basin Platform, a north-trending Pennsylvanian positive area located southeast of the Pedernal Uplift, has been interpreted recently to have been the product of dextral transpression (Yang and Dorobek, 1995).

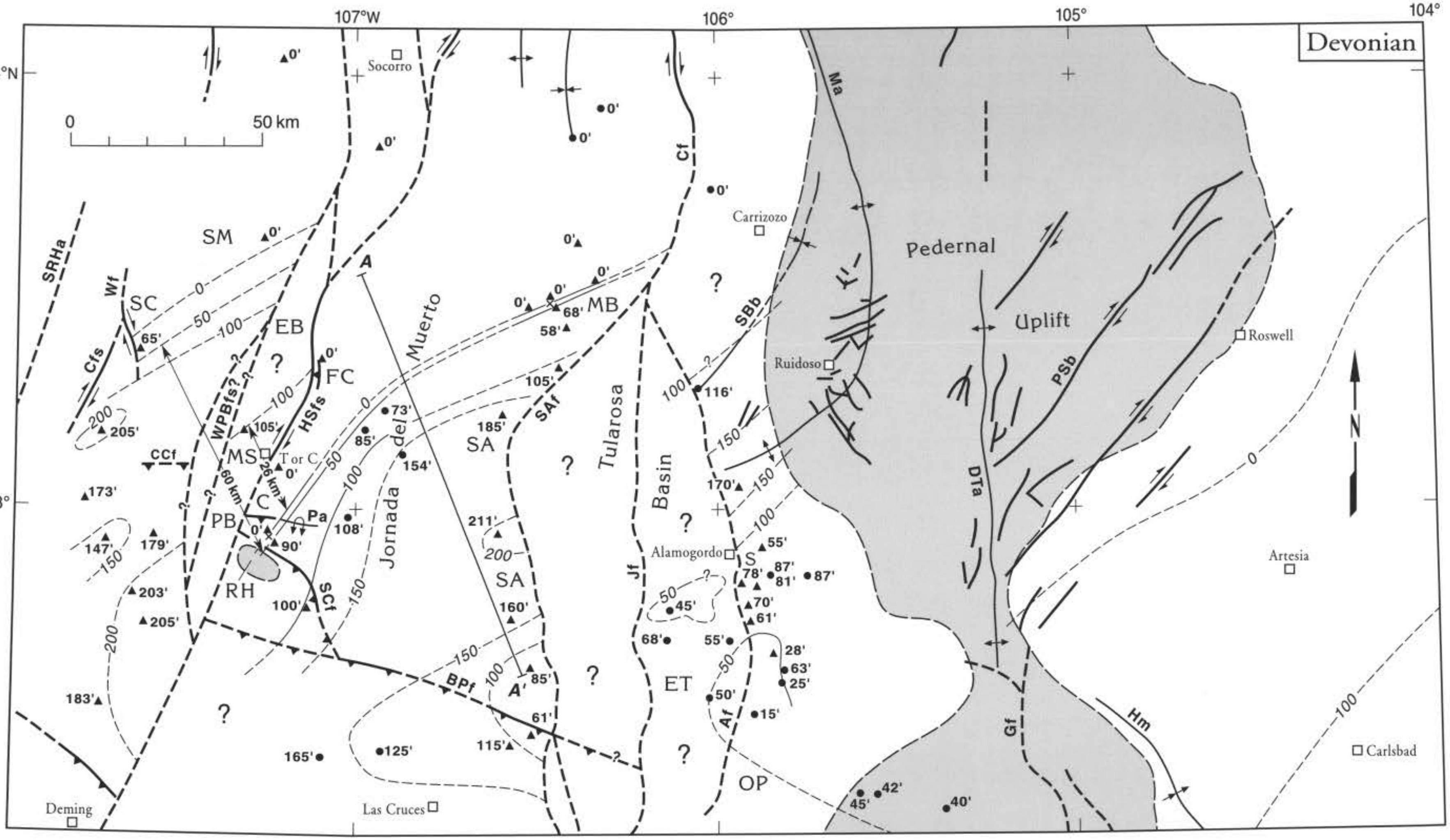
All isopach maps for early Paleozoic units examined in this study show possibly large dextral deflections across the Pedernal Uplift. For several reasons, however, interpretation of the origin of these deflections is equivocal. First, we have not yet compiled and contoured the thickness data for lower Paleozoic strata east of the Pedernal Uplift. Our maps in this area are based on the isopach contours of earlier workers (Greenwood et al., 1977; Hayes and Cone, 1975). Although the isopach maps of these workers are in reasonable agreement (see also Frenzel et al., 1988), their control points were not published. Second, the near parallelism between the zero contours on these maps (Figs. 3, 5, 6 and 7) and the margin of the Pedernal Uplift southwest of Roswell complicates estimation of deflection across the uplift. For example, if the actual truncation of the zero isopachs by the rising Pedernal Uplift were near Roswell instead of southwest near the latitude of Artesia, only a modest dextral deflection relative to the Sacramento–Otero Platform block would be required.

For these reasons, we will forego estimating the deflection for the Pedernal Uplift until more work is done. We note that lateral separation of aeromagnetic anomalies along the Duncan–Tinnie trend seem to allow no more than ~15 km of dextral slip (Kucks et al., 2001). Thus, dextral deflections of early Paleozoic isopachs greater than ~15 km thus probably originated syndepositionally. Dextral strike-slip in the Pedernal Uplift area would likely be mostly late Paleozoic in age, as Laramide deformation in this area is clearly subordinate in magnitude to that of the Ancestral Rocky Mountain orogeny.

Tularosa Basin area

The Neogene Tularosa Basin and adjacent areas have experienced both Laramide and Ancestral Rocky Mountain tectonism. Examples of Laramide structures include: (1) the Chupadera fault, which enters the north end of the basin, exhibits localized folding of the San Andres Formation near left-stepping bends in the fault, consistent with dextral slip (Cather, 1999, table 1); (2) the Sierra Blanca Basin borders the Tularosa Basin on the northeast and contains thick deposits of Eocene age (Cather, 1991, this guidebook); (3) the Mescalero anticlinorium, a complexly faulted, folded, and intruded structural arch, is probably late Laramide in origin (Kelley, 1971; note, however, that parts of the structure coincide with the western margin of the Pedernal Uplift and thus also may have been active in the late Paleozoic); to the south, the Mescalero anticlinorium bends southwestward near Ruidoso where it forms the steep southeast margin of the Sierra Blanca Basin near where it intersects the Tularosa Basin; and (4) a localized zone of thrust faults and associated fault-propagation folds occurs along the western range-front of the Sacramento Mountains, parallel to and immediately east of the basin-bounding Alamogordo fault (Pray, 1961). These low-angle contractile structures differ in style from the steep faults and associated folds that characterize late Paleozoic structures elsewhere in the range, and verge in opposition to the expected west-down sense of late Paleozoic deformation that might accompany the transition from the Pedernal Uplift (on the east) to the Orogrande Basin (to the west). Constrained to be post-Pennsylvanian and pre-late Eocene (Pray, 1961), these thrust faults may be Laramide. If so, the Tularosa Basin may have been structurally and topographically positive during the Laramide, and subsequently inverted during mid-Tertiary extension.

FIGURE 7. Isopach map of Devonian strata. Control points west of Pedernal Uplift are from Kottlowski (1963), Foster (1978), and King and Harder (1985). Pinchout exposures are from Bachman (1968) and Seager and Mack (in press). Contours east of the Pedernal Uplift are from Greenwood et al. (1977). Contour interval is variable. Structures and localities are listed in caption of Figure 3.



▲—?—▲ Pre-rift fault, dashed where approximately located or where pre-rift ancestry uncertain; queried where inferred; barbs on upthrown blocks of Laramide thrust or reverse faults; arrows indicate known sense of Laramide lateral slip.

Pre-rift folds
- anticline
- syncline
- monocline
- overturned anticline

Late Paleozoic uplifts of Ancestral Rocky Mountains. Pedernal uplift delineated by zero isopach of Pennsylvanian rocks (Meyer, 1966, fig. 48). Red Hills (RH) area of mild uplift shown where Pennsylvanian strata locally overlie El Paso Formation (Seager and Mack [in press]).

Control Points

▲ outcrop ● well × exposure of pinchout

—100— — –?– Isopach contour (feet); solid where trend and location are well constrained; dashed where trend uncertain; queried where trend and location uncertain.

←40 km→ Deflection estimate using best-defined isopach contours

The modern Tularosa Basin approximates the geometry of the late Paleozoic Orogrande Basin, particularly along its eastern border. The structural style of the Orogrande Basin is poorly known, largely because of exploration restrictions on White Sands Missile Range. The Sacramento Mountains encompass part of the late Paleozoic shelf between the Orogrande Basin and the Pedernal Uplift (Raatz, this volume). In the Sacramentos, a beautifully preserved set of late Paleozoic structures is present, including a perplexing array of normal faults, reverse faults, and major folds, most of which are north-trending (Pray, 1961). One of these structures, the Fresnal fault, is associated with en-echelon, northwest-plunging folds (Pray, 1961; Otte, 1959) that are suggestive of dextral components of slip on the fault (Cather, 2000a, 2001). Modest dextral separation (~1.6 km) of a structural culmination on the north-striking Bug Scuffle fault (Pray, 1961) and lack of major offsets of aeromagnetic anomalies (Kucks et al., 2001) suggest that dextral slip in the Sacramento Mountains area was probably not large.

The Bliss–El Paso (Fig. 3), Montoya (Fig. 5) and Fusselman (Fig. 6) isopach maps all display well-defined contour lines that deflect dextrally across the Tularosa Basin. The isopach map for Devonian strata (Fig. 7) does not contain well-defined contours east of the Tularosa Basin, and therefore is ambiguous relative to the presence or absence of deflections. Magnitude of well-defined deflections are 66 km (600 ft contour of Bliss–El Paso), 55 km (500 ft contour of Blixx–El Paso), 45 km (100 ft contour of Bliss–El Paso), 37 km (400 ft contour of Montoya), and 40 km (zero contour of Fusselman). Of these estimates, the 66 km and 55 km estimates are probably the least reliable due to the greater east–west distance that separates their control points across the basin. The other estimates are in reasonable agreement and suggest ~40 km dextral deflection across the Tularosa Basin. Most of this is accommodated in the western part of the basin (possibly along the Jarilla and/or San Andres faults), as apparent isopach continuity across the Alamogordo fault on the maps for Montoya, Fusselman, and Devonian strata argues strongly against significant strike slip on this fault.

There is no sedimentologic evidence yet reported for early Paleozoic strata in southern New Mexico to suggest that major deflections, such as are evident across the Tularosa Basin, are of original sedimentary origin. Sharp, nearly right-angle deflections (as are required by the Bliss–El Paso 100 ft contour in the northern Tularosa Basin), if of a sedimentary origin such as a deeply embayed shoreline, should be reflected in paleocurrents or facies relationships (clastic/carbonate ratios, grain size). The Bliss–El Paso outcrops near Mockingbird Gap show no anomalous characteristics (Bachman, 1968) that might suggest the adjacent deflection originated largely as a shoreline embayment.

We thus infer that the ~40 km deflection across the western Tularosa Basin may be largely or entirely of tectonic origin. It is probable that both Laramide and late Paleozoic dextral faults contributed to this deflection, but their relative contributions are not known. Interestingly, the deflection across the Tularosa Basin matches closely with the well-constrained 37 km dextral separation of Proterozoic lithologies and structures across the Picuris–Pecos fault to the north (Miller et al., 1963; Karlstrom and Daniel, 1993; Daniel et al., 1995). Given the probable north–south interconnectivity between these fault systems (Fig. 1), we note that the timing constraints (post–early Paleozoic) for dextral deflections in the Tularosa Basin, if correct, may obviate the need for significant Proterozoic dextral slip on the Picuris–Pecos fault.

The aeromagnetic anomaly map of Kucks et al. (2001) suggests that the Jarilla fault probably was the principal dextral fault in the Tularosa Basin. The possibility of major dextral slip on the Jarilla fault may have implications for the southeastward extension of the Bear Peak fault, the frontal thrust of the Laramide Rio Grande Uplift (Seager and Mack, 1986; Seager et al., 1997). The Bear Peak fault extends along strike to the southeast, where it is last exposed in the southern San Andres Mountains (Fig. 1). Weak gravity (Keller and Cordell, 1983) and aeromagnetic (Kucks et al., 2001) anomalies suggest the fault continues southeastward across the western Tularosa Basin block and terminates against the Jarilla fault. The Bear Peak fault, however, is not present farther along trend in the Orogrande area of the eastern Tularosa Basin or in the Otero Platform area (Black, 1976). A northwest-striking, northeast-directed thrust fault of probable Laramide age, here termed the McGregor fault, is present east of the Jarilla fault in the southeastern Tularosa Basin (Fig. 1; U.S. Army, 1998; Broadhead, this guidebook). The 40 km dextral separation between these faults is compatible with the deflection estimates described above, and suggests that the Bear Peak and McGregor faults (or their possible pre-Laramide precursors) may have been originally contiguous.

The Hot Springs and West Palomas Basin fault systems

Where it is best exposed near Truth or Consequences (T or C), the Hot Springs fault system consists of a 15-km wide system of faults, the most prominent of which is the Hot Springs–Walnut Canyon fault that forms the easternmost strand of the system (Harrison and Chapin, 1990; Harrison and Cather, in press). The Hot Springs fault system is marked by a regional geophysical anomaly more than 160 km in length. It is conspicuous on the aeromagnetic anomaly map of Kucks et al. (2001).

Harrison and Chapin (1990) argued that a variety of disparate stratigraphic terranes, geophysical anomalies, and structures could be rematched across the Hot Springs fault system by restoring ~26 km of Laramide dextral slip on the fault. These evidences for lateral separation were disputed by Seager and Mack (in press), who interpreted only local reverse-slip of Laramide age on the Hot Springs fault. Palinspastic reconstructions were further explored by Harrison and Cather (in press), who also analyzed the dextral deflections of zero isopach lines for lower Paleozoic units across the Hot Springs system and other possible faults buried beneath the Palomas and Engle basins to the west. In this study, we expand the analysis of lower Paleozoic stratigraphy to include the non-zero isopach lines as well.

The nearest control points west of the Jornada del Muerto block are located in the Mud Springs Mountains. Between these areas, the only major structure is the Hot Springs fault system, across which the best-constrained isopach deflections are ~26 km (600 ft isopach of Bliss–El Paso; Fig. 3), <28 km (zero isopach of Fusselman; Fig. 6), and ≥26 km (zero isopach of Devonian strata).

Isopach comparison between the Jornada del Muerto block and the southern San Mateo Mountains area places constraints on deflections across the Engle Basin of the rift, the eastern part of which contains the Hot Springs fault system. The best constrained deflections between the Jornada del Muerto block and the San Mateos are ~32 km (200 ft isopach of Bliss–El Paso; note that this is the only contour line west of the Jornada del Muerto block for which the trend is reasonably well defined), and ~36 km (zero isopach of Montoya). Of each of these deflections, ~26 km is probably attributable to the Hot Springs fault system.

Control points on the Jornada del Muerto block and the Sierra Cuchillo span the intervening Palomas Basin, which includes the Hot Springs fault system in its eastern part. The best constrained deflection estimates between the Jornada del Muerto block and the Sierra Cuchillo are 57 km (zero isopach of Fusselman) and 60 km (50 ft isopach of Devonian strata). The *trend* of isopachs in the Sierra Cuchillo (with the exception of the 200 ft contour of the Bliss–El Paso), however, is poorly constrained.

Invocation of a sedimentary origin for the Bliss–El Paso and Devonian strata isopach deflections between the Caballo and Mud Springs Mountains would require a sharp bend (90° or greater) from the regional southwest trend to a northerly trend. We note that no such sharp bends or northerly trends are evident for these units elsewhere in the study area. Additionally, no anomalous sedimentary facies or grain-size characteristics that might be expectable near such a sharply embayed pinchout have been reported from the Mud Springs Mountains (Maxwell and Oakman, 1986, 1990). The ~26 km deflection between the Caballo and Mud Springs Mountains is compatible with the determinations of Harrison and Chapin (1990) and Harrison and Cather (in press) for dextral slip along the Hot Springs fault system, based on a variety of geologic and geophysical criteria. We therefore interpret the isopach deflections described above to be the product of dextral slip on the Hot Springs fault system. These ~26 km isopach deflections, if resolved along the north–northeast strike of the fault system, suggest about 30 km of dextral slip.

Pennsylvanian sedimentation and the nature of the basal Pennsylvanian unconformity in southern New Mexico were certainly influenced by Ancestral Rocky Mountain orogenesis. The T or C area, however, was located on the relatively stable western shelf of the Orogrande Basin and was characterized sedimentologically by deposition of mostly limestone and shale (Kottlowski, 1960, plate 5). Clastic ratios and sand-shale ratios are reasonably similar throughout the region near T or C (Kottlowski, 1960). Two areas near the Hot Springs fault system display evidence for local relief at the base of the Pennsylvanian section. In the Red Hills area, Pennsylvanian strata overlie the El Paso Formation (Seager and Mack, in press), suggesting modest (~300 m) depths of Late Mississippian to Early Pennsylvanian erosion due to southwest-up faulting or flexure across the southern Caballo fault. North of a strand of the Hot Springs fault system on a local structural block in the Mud Springs Mountains, Devonian strata and the uppermost Montoya Formation are cut out beneath basal Pennsylvanian beds, and the overlying Pennsylvanian Red House Formation is somewhat thinner there than across the fault to the south, giving a total stratigraphic thinning of ~100 m (Maxwell and Oakman, 1986, 1990; Harrison and Cather, in press). In the Mud Springs Mountains, however, it is not clear if these differing stratigraphies resulted from differential Pennsylvanian deformation or subsequent Laramide strike-slip juxtaposition, or both. Although we acknowledge the possibility of Pennsylvanian dip-slip or strike-slip tectonism in the T or C area, we feel that such tectonism was relatively weak, as shown by lack of rapid lateral facies transitions, scarcity of conglomerate, and lack of intraformational angular unconformities in Pennsylvanian strata. Furthermore, along structural strike to the north, the sense of lateral slip on late Paleozoic structures was sinistral (Beck and Chapin, 1994; Karlstrom et al., 1997), opposite to the dextral separation on the Hot Springs fault system.

We question the conclusions of Furlow (1965) and Kelley and Furlow (1965), who interpreted the dextral deflection of Cambro–Ordovician pinchouts across the Engle Basin to be the result of broad Late Mississippian to Early Pennsylvanian arching and erosion in the Caballo–Fra Cristobal area. Arguments against this model are: (1) the arching hypothesis would predict systematic thinning of Pennsylvanian strata over the Caballo–Fra Cristobal area, which is not observed in isopach maps (Kottlowski, 1960, 1963); (2) pre-Pennsylvanian arching and erosion cannot explain why similar deflections exist for Fusselman and Devonian pinchouts between the Jornada del Muerto block and the Sierra Cuchillo; of these two, only the location of the Devonian pinchout was influenced by the basal Pennsylvanian unconformity; (3) if arching and beveling prior to deposition of Pennsylvanian strata were important, isopach contours near the beveled edge of the Bliss–El Paso would be expected to trend northwest on the western flank of the arch (Kelley and Furlow, 1965, fig. 1); the only well-constrained contour in this area, however, trends northeast (Fig. 3); and (4) lack of rapid facies changes, pronounced grain-size trends and intraformational angular unconformities in Pennsylvanian sedimentary rocks near the Caballo–Fra Cristobal area all argue against the presence of a late Paleozoic arch.

Crustal deformation in the T or C area was much more profound during the Laramide orogeny than during the earlier Ancestral Rocky Mountain event. Local topographic relief associated with Eocene paleocanyons in the region was at least one kilometer (Seager et al., 1997), and exposure of Precambrian rocks during this time indicates at least 4 km of structural relief between basins and uplifts. Dextral shear indicators along the Hot Springs fault system near T or C are widespread in strata as young as Late Cretaceous (Harrison and Cather, in press; E. Erslev, oral commun., 2001). The dextral Chloride fault, which lies west of and parallel to the Hot Springs fault system (Fig. 1), cuts rocks as young as late Eocene and is buried by an unfaulted ash-flow tuff dated 34.93 ± 0.04 Ma (Harrison, 1989; Harrison and Cather, in press). Because late Paleozoic deformation was relatively mild in the vicinity of the Hot Springs fault system, we infer that most or all of the dextral separation along the fault is Laramide.

West of the Jornada del Muerto block, the magnitude of individual isopach deflections increases with increased spacing between control points. The geographically closest juxtaposition of control points brackets the Hot Springs fault system between the Caballo and Mud Springs Mountains, as described above. The next most closely constrained deflections are between the Fra

Cristobal and San Mateo Mountains. These right-angle, 32–36 km deflections encompass the Engle Basin, which includes the Hot Springs fault system in its eastern part. Of these, the northeasterly trend of the 200 ft contour of the Bliss–El Paso is reasonably well defined on both sides of the Engle Basin. An unbroken contour across the Engle Basin would require a local north-northwest trend. Because such trends are undefined elsewhere on the Bliss-El Paso isopach map (Fig. 3), we suspect this 32 km deflection is of mostly tectonic, probably Laramide, origin. If so, when resolved on faults of north–northeast strike, this deflection would correspond to ~37 km of dextral slip, ~30 km of which is attributable to the Hot Springs fault system.

The broadly constrained 57–60 km deflections of the Fusselman and Devonian pinchouts across the Palomas Basin also include the Hot Springs fault system in its eastern part. The origin of the additional dextral deflections beyond the 26 km value that we attribute to the Hot Springs fault system is unknown. Because the trend of the Fusselman and Devonian pinchouts west of the Palomas Basin are undefined, a syndepositional origin is possible. Alternatively, because very little is known about the subsurface geology of the Palomas Basin it is also possible that additional Laramide faults lie buried beneath it (conjecturally represented on our maps as the west Palomas Basin fault system). Although the existence of buried Laramide strike-slip faults beneath the Palomas Basin is speculative, the net dextral deflections of lower Paleozoic pinchouts across the basin (57–60 km) are comparable with the maximum allowable offsets of Mesozoic piercing lines in the Albuquerque Basin to the north (40–60 km; Cather, 1999). Thus, if these additional deflections west of the Hot Springs fault system are of tectonic origin, they are plausibly Laramide.

COMPARISON WITH PIERCING-LINE CONSTRAINTS IN NORTHERN NEW MEXICO

Virtually all workers who have studied the Proterozoic rocks of northern New Mexico, and/or the aeromagnetic anomalies that relate to them, have agreed that major, north-striking, dextral discontinuities are present in basement rocks in this area (Miller et al., 1963; Bauer and Ralser, 1995; Karlstrom and Daniel, 1993; Daniel et al., 1995; Chapin, 1983; Cordell and Keller, 1984, Woodward, 2000; Pollock et al., in press). There is considerably less agreement, however, as to when these dextral displacements occurred. They have been interpreted to have formed mostly in the Proterozoic (Miller et al., 1963; Yin and Ingersoll, 1997), mostly in the late Paleozoic (Woodward et al., 1999), and mostly during the Laramide (Karlstrom and Daniel, 1993; Daniel et al., 1995; Chapin and Cather, 1981, Cather, 1999).

Recent attempts to utilize Mesozoic stratigraphic piercing lines to delimit the Laramide component of the dextral slip have produced widely differing estimates. Cather (1999) concluded that, because of the effects of widely separated control points and broad areas of Tertiary erosion, most Mesozoic piercing lines were imprecise and that the range of allowable net dextral slip was ~33–110 km. In contrast, in a series of papers and abstracts, Woodward et al. (1996), Woodward et al. (1997a, b, c), Lucas et al. (1997), and Lucas and Woodward (2001) argued that Mesozoic piercing lines allow for only small amounts of Laramide dextral slip (generally 5–20 km, except for the 5–25 km estimate of Woodward et al., 1997c). Because of this limitation on Laramide slip, Woodward et al. (1999) reasoned that the remaining displacements of Proterozoic rocks in northern New Mexico (~125 km) must therefore have occurred in the late Paleozoic. We disagree with this rationale, particularly with regard to the limitations on Laramide slip. Rather than restate the details of Mesozoic piercing-line constraints on Laramide dextral slip (these are elucidated in the preceding references and the Discussion/Reply series by Woodward, 2000, and Lucas et al., 2000), we will instead point out some of the methodologies and logical constructs that, in our opinion, have led to the erroneous interpretations presented in these papers (herein collectively cited as Woodward et al.). It is hoped that this more generalized discussion will prove educational to those geoscientists who, though perhaps disinterested in the details of the Mesozoic piercing-line debate, nonetheless are curious how such large interpretational disparities could result from geologists studying similar strata.

Utilization of obsolescent or generalized isopach maps. Woodward et al. commonly cite isopach maps as old as the 1950s to support of their interpretations (McKee et al., 1956; Ash, 1958) despite great advances in knowledge of outcrop and (particularly) subsurface geology in the intervening decades. Woodward et al. made little or no attempt to modify these maps to reflect recent data, particularly in the critical subsurface of the Albuquerque Basin (cf. Cather, 1999). Remarkably, the recent Jurassic isopach maps of Lucas et al. (1985) were not utilized by Woodward et al., despite the fact that these maps contradict aspects of the earlier work of McKee et al. (1956) in several important ways (Cather, 1999; Cather and Karlstrom, 2000). Other publications that bear on critical issues such as the trend of the Todilto pinchout in eastern New Mexico (Lucas et al., 1985, fig. 8) and the southern limit of the Morrison Formation in eastern New Mexico (Lucas, 1991; Hunt and Lucas, 1987; Hayden et al., 1990) have been variously ignored or reinterpreted by Woodward et al. Other sources of stratigraphic data cited by Woodward et al., such as the map of Black (1979), have been shown to be too generalized to provide useful piercing lines (Cather, 2000b).

Lack of discrimination between interpretations that are permissive and those that are definitive. The location and/or trend of all of the Mesozoic piercing lines cited by Woodward et al. are in places undefined due to the effects of control-point spacing and Tertiary erosion. Rather than estimating the range of possible interpretations where these areas of poor control coincide with Laramide faults as did Cather (1999), Woodward et al. simply cited obsolescent maps that connected between areas of control with unbroken contours, despite the fact that some control points are separated by hundreds of kilometers and by major intervening faults. Interpretations based on such contouring schemes are permissive, but are clearly nondefinitive. Interestingly, the most closely constrained dextral deflections yet identified in northern New Mexico (13 km Jurassic deflection across Defiance monocline of Kelley, 1967; 20–33 km Gallup Sandstone deflection across Sand Hill–Nacimiento fault system of Cather, 1999) have not been addressed by Woodward et al., despite the fact that the combined magnitude of these deflections alone exceeds the net 5–20 km slip estimate of Woodward et al.

Inconsistencies between slip estimates and purported piercing-line constraints. Woodward et al. claimed that Mesozoic piercing lines in northern New Mexico allow only 5–20 km of net Laramide dextral slip. However, the various maps they present in support of their hypothesis, if taken at face value, all show zero offset. Even if these maps could be shown to be correct, why do they allow 5–20 km of dextral slip, but not 3, 30, 50 or 80 km? What specific attributes of these maps can be construed to support only 5–20 km of Laramide dextral slip? Based on the more rigorous analysis of Cather (1999) in which a quantitative assessment of the uncertainties involving Mesozoic piercing lines was attempted, it seems that an empirical basis for the slip estimate of Woodward et al. does not exist.

Cather (1999) inferred that the net 52 km dextral separation of Proterozoic piercing lines across the Picuris–Pecos and Tusas–Picuris faults may represent minimum Laramide slip, in order to compensate for sinistral components related to late Paleozoic deformation and Miocene rifting. His interpretation of sinistral, north-striking, Ancestral Rocky Mountain faults in northern New Mexico was based on the observations of Beck and Chapin (1994) and Karlstrom et al. (1997). Using this rationale in concert with the minimum 33 km separation derived from Mesozoic constraints on other faults, Cather (1999) estimated the minimum Laramide net dextral slip in northern New Mexico was ~85 km. Subsequent work, however, has demonstrated dextral components also exist on some north-striking, late Paleozoic faults in New Mexico (Cather, 2000a, 2001). In view of these later observations, it is probable that the dextral separations of Proterozoic rocks in northern New Mexico resulted primarily from an as-yet undetermined combination of Laramide, late Paleozoic, and (possibly) Proterozoic dextral components. The relative importance of Laramide versus Ancestral Rocky Mountain contributions to the net 52 km dextral separation on the Tusas–Picuris and Picuris–Pecos faults is thus in need of further study.

Dextral deflections of lower Paleozoic isopachs across the Tularosa Basin (~40 km) and west of the Jornada del Muerto block (~57–60 km) yield a net regional dextral deflection of ~100 km. These estimates do not include possible additional dextral deflections across the Pedernal Uplift. It is thus possible that post–early Paleozoic slip may account for most or all of the Proterozoic separations in northern New Mexico.

The data analyzed in this report do not establish the relative importance of Laramide versus Ancestral Rocky Mountain dextral deformation in southern New Mexico, particularly along the Picuris–Pecos trend in the Tularosa Basin area. While much work remains to be done, a consistent regional pattern of demonstrable or permissible dextral separations on north-striking faults seems to be evident throughout New Mexico for all rocks yet analyzed (lower Paleozoic, this report; Proterozoic, Jurassic, and Cretaceous, Cather, 1999, and references therein). For piercing lines in these rocks of diverse ages, the following generalizations apply: (1) all *allow* cumulative dextral strike-slip separations of ~100 km, and none *require* less; (2) there are no unique interpretations that demand little or no offset for any of these rocks. Demonstrable, major dextral deflections across faults exist locally in isopach patterns of sedimentary rocks of early Paleozoic, Jurassic, and Late Cretaceous age, although many of these deflections cannot be proven to be tectonic in origin. However, if these systematic deflections are not tectonic but originated instead as syndepositional "meandering shore lines and other facies trends" (Ingersoll, 2000, p. 796), why are they uniformly dextral?

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REFERENCES

Ahlen, J., 1998, Thimble Canyon Prospect; *in* Cather, M., ed., Frontier and underexplored basins of New Mexico: Petroleum Technology Transfer Council, Southwest Region Focused Technology Workshop, 16 p.

Aldrich, M. J., Jr., 1972, Tracing a subsurface structure by joint analysis: Santa Rita-Hanover axis, southwestern New Mexico [Ph.D. dissertation]: Albuquerque, University of New Mexico, 106 p.

Aldrich, M. J., Jr., 1976, Geology and flow directions of volcanic rocks of the North Star Mesa quadrangle, Grant County, New Mexico; *in* Elston, W. E. and Northrop, S. A., eds., Cenozoic volcanism in southwestern New Mexico, New Mexico Geological Society, Special Publication 5, p. 76–81.

Ash, H. O., 1958, The Jurassic Todilto Formation of New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 63 p.

Bachman, G. O., 1968, Geology of the Mockingbird Gap quadrangle, Lincoln and Socorro counties, New Mexico: U.S. Geological Survey, Bulletin 1826, 40 p.

Baltz, E. H. and Myers, D. A. 1999, Stratigraphic framework of upper Paleozoic rocks, southeastern Sangre de Cristo Mountains, New Mexico with a section on speculations and implications for regional interpretation of ancestral Rocky Mountains paleotectonics: New Mexico Bureau of Mines and Mineral Resources, Memoir 48, 269 p.

Bauer, P. W. and Lozinsky, R. P., 1991, The Bent dome—Part of a major Paleozoic uplift in southern New Mexico: New Mexico Geological Society, 42nd Field Conference, Guidebook, p. 174–181.

Bauer, P. W. and. Ralser, S., 1995, The Picuris-Pecos fault—repeatedly reactivated from Proterozoic(?) to Neogene: New Mexico Geological Society, 46th Field Conference, Guidebook, p. 111–115.

Beck, W. C. and Chapin, C. E., 1994, Structural and tectonic evolution of the Joyita Hills, central New Mexico: implications of basement control on Rio Grande rift; *in* Keller,G. R. and Cather, S. M., eds., Basins of the Rio Grande rift: structure, stratigraphy and tectonic setting: Geological Society of America, Special Paper 291, p. 187–205.

Black, B. A., 1975, Geology and oil and gas potential of the northeast Otero Platform area, New Mexico: New Mexico Geological Society 26th Field Conference, Guidebook, p. 323–333.

Black, B. A., 1976, Tectonics of the northern and eastern parts of the Otero Platform, Otero and Chaves Counties, New Mexico: New Mexico Geological Society, Special Publication 6, p. 39–45.

Black, B. A., 1979, Structure and stratigraphy of the Hagan embayment: A new look: New Mexico Geological Society 30th Field Conference, Guidebook, p. 101–105.

Bowsher, A. L., 1991, The basement of the Sacramento Mountains, New Mexico Geological Society, 42nd Field Conference, Guidebook, p. 81–89.

Broadhead, R. F., this guidebook, Petroleum geology of the McGregor Range, Otero County, New Mexico: New Mexico Geological Society 53rd Field Conference, Guidebook.

Budnik, R. T., 1986, Left-lateral deformation along the Ancestral Rocky Mountains: Implications for late Paleozoic plate motions: Tectonophysics, v. 132, p. 195–214.

Cather, S. M., 1991, Stratigraphy and provenance of Upper Cretaceous and Paleogene strata of the western Sierra Blanca Basin, New Mexico, New Mexico Geological Society, 42nd Field Conference, Guidebook, p. 265–275.

Cather, S. M., 1999, Implications of Jurassic, Cretaceous, and Proterozoic piercing lines for Laramide oblique-slip faulting in New Mexico and rotation of the Colorado Plateau: Geological Society of America Bulletin, v. 111, p. 849–868.

Cather, S. M., 2000a, Preliminary analysis of the Fresnal fault system; a major dextral normal fault of late Pennsylvanian age in south-central New Mexico: American Association of Petroleum Geologists Bulletin, v. 84, p. 1237.

Cather, S. M., 2000b, Implications of Jurassic, Cretaceous and Proterozoic piercing lines for Laramide oblique-slip faulting in New Mexico and rotation of the Colorado Plateau: Reply: Geological Society of America Bulletin, v. 112, p. 790–795.

Cather, S. M., 2001, North–south differences in timing and style of ancestral Rocky Mountain deformation, southwestern North America: Geological Society of America Abstracts with Programs, v. 33, no. 5, p. 45.

Cather, S. M. and Karlstrom, K. E., 2000, Implications of Jurassic, Cretaceous and Proterozoic piercing lines for Laramide oblique-slip faulting in New Mexico and rotation of the Colorado Plateau: Reply: Geological Society of America Bulletin, v. 112, p. 785–788.

Chapin, C. E., 1983a, An overview of Laramide wrench faulting in the southern Rocky Mountains with emphasis on petroleum exploration; *in* Lowell, J. D., ed., Rocky Mountain foreland basins and uplifts: Denver, Rocky Mountain Association of Geologists, p. 169–180.

Chapin, C. E. and Cather, S. M., 1981, Eocene tectonics and sedimentation in the Colorado Plateau-Rocky Mountain area; *in* Dickinson, W. R. and Payne, W. D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 173–198.

Clemons, R. E., 1991, Petrography and depositional environments of the Lower Ordovician El Paso Formation: New Mexico Bureau of Mines and Mineral Resources, Bulletin 125, 68 p.

Cordell, L. and Keller, G. R., 1984, Regional structural trends inferred from gravity and aeromagnetic data in the New Mexico–Colorado border region: New Mexico Geological Society 35th Field Conference, Guidebook, p. 21–23.

Daniel, C. G., Karlstrom, K. E., Williams, M. L. and Pedrick, J. N., 1995, The reconstruction of a middle Proterozoic orogenic belt in north-central New Mexico, U.S.A.: New Mexico Geological Society 46th Field Conference Guidebook, p. 193–200.

Foster, R. W., 1978, Oil and gas evaluation of White Sands Missile Range and Fort Bliss Military Reservation, south-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 92, 60 p.

Frenzel, H. N., Bloomer, R. R., Cline, R. B., and eleven others, 1988, The Permian Basin region; *in* Sloss, L. L., ed., Sedimentary cover—North American craton: U.S.: Geological Society of America, The Geology of North America, v. D-2, p. 261–306.

Furlow, J. W., 1965, Geology of the San Mateo Peak area, Socorro County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 83 p.

Galley, J. E., 1958, Oil and geology in the Permian Basin of Texas and New Mexico; *in* Habitat of Oil: American Association of Petroleum Geologists, p. 395–446.

Greenwood, E., Kottlowski, F. E. and Thompson, S., 1977, Petroleum potential and stratigraphy of Pedregosa Basin: comparison with Permian and Orogrande Basins: American Association of Petroleum Geologists Bulletin, v. 61, p. 1448–1469.

Harrison, R. W., 1994, Winston graben: stratigraphy, structure, and tectonic setting; *in* Keller, G. R. and Cather, S. M., eds., Basins of the Rio Grande rift: structure, stratigraphy, and tectonic setting: Geological Society of America, Special Paper 291, p. 227–240.

Harrison, R. W., 1989, Exotic blocks within the early Tertiary Rubio Peak Formation in the north-central Black Range, New Mexico: Occurrence, insights into post-tectonic emplacement activity, economic implications and emplacement hypothesis: New Mexico Geological Society 40th Field Conference, Guidebook, p. 99–106.

Harrison, R. W., and Cather, S. M., in press, The Hot Springs fault system: evidence in south-central New Mexico for northward translation of the Colorado Plateau during the Laramide orogeny; *in* Cather, S. M., McIntosh, W. C. and Kelley, S. A., eds., Tectonics, volcanism, and geochronology in the southern Rocky Mountains and Rio Grande rift: New Mexico Bureau of Geology and Mineral Resources, Bulletin 160.

Harrison, R. W. and Chapin, C. E., 1990, A NNE-trending, dextral wrench-fault zone of Laramide age in southern New Mexico: Geological Society of America, Abstracts with Programs, v. 22, p. 327.

Hayden, S. N., Lucas, S. G., Hunt, A. P., and Beck, W. C., 1990, Triassic-Jurassic stratigraphy, Palo Duro Canyon, Sevilleta Grant, Socorro County, New Mexico: New Mexico Geology, v. 12, p. 65, 75.

Hayes, P. T. and Cone, G. C., 1975, Cambrian and Ordovician rocks of southern Arizona and New Mexico and westernmost Texas: U.S. Geological Survey, Professional Paper 873, 98 p.

Hill, J. D., 1956, Paleozoic stratigraphy of the Mud Springs Mountains, Sierra County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 72 p.

Hill, M. L. and Diblee, T. W., Jr., 1953, San Andreas, Garlock, and Big Pine faults, California—A study of their character, history, and tectonic significance of their displacements: Geological Society of America Bulletin, v. 64, p. 443–458.

Hunt, A. P. and. Lucas, S. G., 1987, Southeasternmost outcrops of the Morrison Formation in the Carthage area, Socorro County, New Mexico: New Mexico Geology, v. 9, p. 58–62.

Ingersoll, R. V., 2000, Implications of Jurassic, Cretaceous and Proterozoic piercing lines for Laramide oblique-slip faulting in New Mexico and rotation of the Colorado Plateau: Discussion: Geological Society of America Bulletin, v. 112, p. 796–798.

Jahns, R. H., 1955, Geology of the Sierra Cuchillo: New Mexico Geological Society 6th Field Conference, Guidebook, p. 158–174.

Jones, W. R., Hernon, R. M. and Moore, S. L., 1967, General geology of Santa Rita quadrangle, Grant County, New Mexico: U.S. Geological Survey, Professional Paper 555, 1445 p.

Karlstrom, K. E. and Daniel, C. G., 1993, Restoration of Laramide right-lateral strike slip in northern New Mexico by using Proterozoic piercing points: Tectonic implications from the Proterozoic to the Cenozoic: Geology, v. 21, p. 1193–1142.

Karlstrom, K. E., Chamberlin, R. M., Connell, S. D., Brown, C., Nyman, M., Parchman, M. A., Cook, C. and Sterling, J., 1997, Geology of the Mount Washington 7.5' quadrangle, Bernalillo and Valencia Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report DGM-8, 55 p.

Keller, G. R. and Cordell, L., 1983, Bouguer gravity anomaly map of New Mexico: New Mexico State University Energy Institute, Geothermal Resources of New Mexico, Scientific Map Series, scale 1:500,000.

Kelley, V. C., 1951, Oolitic iron deposits of New Mexico: American Association of Petroleum Geologists Bulletin, v. 35, p. 2199–2228.

Kelley, V. C., 1967, Tectonics of the Zuni-Defiance region, New Mexico and Arizona, New Mexico Geological Society 18th Field Conference, Guidebook, p. 28–31.

Kelley, V. C., 1971, Geology of the Pecos country, southeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 24, 75 p.

Kelley, V. C., 1972, New Mexico lineament of the Colorado Rockies front: Geological Society of America Bulletin, v. 83, p. 1849–1852.

Kelley, V. C. and Furlow, J. W., 1965, Lower Paleozoic wedge edges in south-central New Mexico: New control: Geological Society of America Bulletin, v. 76, p. 689–694.

Kelley, V. C. and Silver, C., 1952, Geology of the Caballo Mountains: University of New Mexico Publications in Geology, no. 4, 286 p.

Kelley, V. C. and Thompson, T. B., 1964, Tectonics and general geology of the Ruidoso-Carrizozo region, central New Mexico: New Mexico Geological Society 15th Field Conference, Guidebook, p. 110–121.

King, W. E. and Harder, V. M., 1985, Oil and gas potential of the Tularosa Basin–Otero Platform–Salt Basin graben area, New Mexico and Texas: New Mexico Bureau of Mines and Mineral Resources, Circular 198, 36 p.

Kottlowski, F. E., 1960, Summary of Pennsylvanian sections in southwestern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 66, 187 p.

Kottlowski, F. E., 1963, Paleozoic and Mesozoic strata of southwest and south-central New Mexico, New Mexico Bureau of Mines and Mineral Resources, Bulletin 79, 100 p.

Kottlowski, F. E., Flower, R. H., Thompson, M. L. and Foster, R. W., 1956, Stratigraphic studies in the San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 1, 132 p.

Kucks, R. P., Hill, P. L. and Heywood, C. E., 2001, New Mexico aeromagnetic and gravity maps and data: a Web site for distribution of data: U.S. Geological Survey, Open-file Report 01-0061, version 1.0, available at: http://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-01-0061/

Lawton, T. W., 2000, Inversion of Late Jurassic–Early Cretaceous extensional faults of the Bisbee Basin, southeastern Arizona and southwestern New Mexico: New Mexico Geological Society 51st Field Conference, Guidebook, p. 95–102.

Lucas, S. G., 1991, Southeasternmost outcrops of the Morrison Formation, Capitan, Lincoln County, New Mexico: New Mexico Geological Society 46th Field Conference, Guidebook, p. 41.

Lucas, S. G., Anderson, O. J. and Black, B. A., 2000, Implications of Jurassic, Cretaceous and Proterozoic piercing lines for Laramide oblique-slip faulting in New Mexico and rotation of the Colorado Plateau: Discussion: Geological Society of America Bulletin, v. 112, p. 789–790.

Lucas, S. G., Cather, S. M., Abbott, J. C. and Williamson, T. E., 1997, Stratigraphy and tectonic implications of Paleogene strata in the Laramide Galisteo Basin, north-central New Mexico: New Mexico Geology, v. 19, p. 89-95.

Lucas, S. G., Kietzke, K. K. and Hunt, A. P., 1985, The Jurassic system in east-central New Mexico: New Mexico Geological Society 36th Field Conference, Guidebook p. 213–242.

Lucas, S. G. and Woodward, L. A., 2001, Jurassic strata in east-central New Mexico and their regional significance: New Mexico Geological Society 52nd Field Conference, Guidebook, p. 203–212.

Mack, G. H., Kottlowski, F. E. and Seager, W. R., 1998, The stratigraphy of south-central New Mexico: New Mexico Geological Society 49th Field Conference, Guidebook, p. 135–154.

Maxwell, C. H. and Oakman, M. R., 1986, A Pennsylvanian unconformity in the Mud Springs Mountains, New Mexico Geological Society 37th Field Conference, Guidebook, p. 4–5.

Maxwell, C. H. and Oakman, M. R., 1990, Geologic map of the Cuchillo quadrangle, Sierra County, New Mexico: U.S. Geological Survey, Geological Quadrangle Map GQ-1686, scale 1:24,000.

Meyer, R. F., 1966, Geology of Pennsylvanian and Wolfcampian rocks in southeast New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 17, 123 p.

McCleary, J. T., 1960, Geology of the northern part of the Fra Cristobal Range, Sierra and Socorro Counties, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 59 p.

McKee, E. D., Oriel, S. S., Swanson, V. E., MacLachlan, M. E., MacLachlan, J. C., Ketner, K. B., Goldsmith, J. W., Bell, R. Y., Jameson, D. J. and Imlay, R. W., 1956, Paleotectonic maps of the Jurassic system: U.S. Geological Survey, Miscellaneous Geological Investigations Map I-175, scale 1:5,000,000.

Miller, J. P., Montgomery, A. and Sutherland, P. K., 1963, Geology of part of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 11, 106 p.

Nelson, E., 1993, Thick- and thin-skinned Laramide deformation, Fra Cristobal Range, south-central New Mexico; *in* Schmidt, C. J., Chase, R. B. and Erslev, E. A., eds., Laramide basement deformation in the Rocky Mountain foreland of the western United States: Geological Society of America, Special Paper 280, p. 257–270.

Otte, C., Jr., 1959, Late Pennsylvanian and Early Permian stratigraphy of the northern Sacramento Mountains, Otero County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 50, 111 p.

Pollock, C. J., Stewart, K. G., Hibbard, J. P., Wallace, L. and Giral, R. A., in press, Thrust-wedge tectonics and strike-slip faulting in the Sierra Nacimiento; *in* Cather, S. M., McIntosh, W. C. and Kelley, S. A., eds., Tectonics, geochronology, and volcanism in the southern Rocky Mountains and Rio Grande rift: New Mexico Bureau of Geology and Mineral Resources, Bulletin 160.

Pray, L. C., 1961, Geology of the Sacramento Mountains escarpment, Otero County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 35, 144 p.

Raatz, W. D., this guidebook, A geologic history of south-central New Mexico: New Mexico Geological Society 53rd Field Conference, Guidebook.

Seager, W. R. and Mack, G. H., 1986, Laramide paleo-tectonics of southern New Mexico; *in* Peterson, J. A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists, Memoir 41, p. 669–685.

Seager, W. R. and Mack, G. H., in press, Geology of the Caballo Mountains, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Memoir 49.

Seager, W. R., Mack, G. H. and Lawton, T. F., 1997, Structural kinematics and depositional history of a Laramide uplift-basin pair in southern New Mexico: Implications for development of intraforeland basins: Geological Society of America Bulletin, v. 109, p. 1389–1401.

Seager, W. R. and Mayer, A. B., 1988, Uplift, erosion, and burial of Laramide fault blocks, Salado Mountains, Sierra County, New Mexico: New Mexico Geology, v. 10, p. 49–53, 60.

Sloss, L. L., 1988, Tectonic evolution of the craton in Phanerozoic time; *in* Sloss, L. L., ed., Sedimentary cover—North American craton: U.S.: Geological Society of America, The Geology of North America, v. D-2, p. 25–51.

U.S. Army, 1998, Mineral and energy resource assessment of the McGregor Range, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 456, 543 p.

Woodward, L. A., 2000, Implications of Jurassic, Cretaceous, and Proterozoic piercing lines for Laramide oblique-slip faulting in New Mexico and rotation of the Colorado Plateau: Discussion: Geological Society of America Bulletin, v. 112, p. 783–788.

Woodward, L. A., Anderson, O. J. and Lucas, S. G., 1996, , Constraints on Laramide right slip along east side of Colorado Plateau, north-central New Mexico: Geological Society of America, Abstracts with Programs, v. 28, no. 7, p. A-374.

Woodward, L. A., Anderson, O. J. and Lucas, S. G., 1997a, Tectonics of the Four Corners region of the Colorado Plateau: New Mexico Geological Society 48th Field Conference, Guidebook, p. 57–64.

Woodward, L. A., Anderson, O. J. and Lucas, S. G., 1997b, Mesozoic stratigraphic constraints on Laramide right slip on the east side of the Colorado Plateau: Geology, v. 25, p. 843–846.

Woodward, L. A., Anderson, O. J. and Lucas, S. G., 1997c, Major Laramide right-slip faults buried beneath the late Cenozoic fill of the Rio Grande rift, New Mexico—fact or fiction?: Geological Society of America, Abstracts with Programs, vol. 29, no. 2, p. 51.

Woodward, L. A., Anderson, O. J. and Lucas, S. G., 1999, Late Paleozoic right-slip faults in the ancestral Rocky Mountains, New Mexico Geological Society 50th Field Conference, Guidebook, p. 149–154.

Yang, K.-M. and Dorobek, S. L., 1995, The Permian Basin of west Texas and New Mexico: Tectonic history of a "composite" foreland basin and its effects on stratigraphic development; *in* Dorobek, S. L. and Ross, G. M., eds., Stratigraphic evolution of foreland basins: Tulsa, SEPM Special Publication no. 52, p. 149–174.

Yin, A. and Ingersoll, R. V., 1997, A model for evolution of Laramide axial basins in the southern Rocky Mountains, USA: International Geology Review, v. 39, p. 1113–1123.

Yuras, W., 1991, Origin of folds in the Permian Yeso Formation, Lincoln, New Mexico: New Mexico Geological Society 42nd Field Conference, Guidebook, p. 165–170.

Fault in the Madera Group near the top of an anticline 2 miles west-southwest of High Rolls, looking west-northwest. This is Fresnal fault, the subject of a study by Howell, et al. (this volume). Photo from Darton (1928).