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2005, pp. 93-104. https://doi.org/10.56577/FFC-56.93

in:

Geology of the Chama Basin, Lucas, Spencer G.; Zeigler, Kate E.; Lueth, Virgil W.; Owen, Donald E.; [eds.], New Mexico Geological Society 56th Annual Fall Field Conference Guidebook, 456 p. https://doi.org/10.56577/FFC-56

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REGIONAL TECTONIC INFERENCES FOR THE 1.4 GA–HOLOCENE LATERAL SLIP HISTORY OF THE PICURIS–PECOS AND RELATED FAULTS, NORTHERN NEW MEXICO

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Abstract.—Dextral discontinuities evident from analysis of aeromagnetic maps for northern New Mexico, corresponding primarily to the north-striking Picuris–Pecos, the Tusas–Picuris, and the Nacimiento fault systems, together yield at least ~55 km and perhaps as much as ~90 km of net dextral separation. A strike-slip origin for these separations, however, has been clearly demonstrated by geologic mapping only for the Picuris–Pecos fault and, less concisely, for the Tusas–Picuris fault. The age of the Picuris–Pecos fault is younger than ~1.45 Ga because it cuts dated foliations of that age in the Picuris Mountains. The lack of mylonites along the Picuris–Pecos fault also indicates it is not older than ~1.2–0.8 Ga, the age when the basement rocks of the Sangre de Cristo Mountains last cooled through temperatures characteristic of the brittle-ductile transition (300–200°C).

To help unravel the reactivation history of the Picuris–Pecos and related faults, the directions of horizontal shortening and/or extension were analyzed for the eight major deformations that have affected the region from 1.4 Ga to the Holocene. For each of these eight tectonic episodes, the resolved lateral shear sense (dextral or sinistral) for north-striking faults in northern New Mexico was inferred. Although there is no direct evidence for Proterozoic slip on the Picuris–Pecos or related faults, such slip seems probable given that Phanerozoic movements often reactivated older structures. Mesoproterozoic slip (~1.4 Ga, ~1.1 Ga) was potentially sinistral based on regional deformation patterns and the postulated long-lived contractional plate margin along southern Laurentia. Neoproterozoic slip (~0.8 Ga) would have been extensional, with a possible sinistral component. Possible Cambrian slip accompanying the opening of the southern Oklahoma aulacogen would have been dextral but of small magnitude (a few km). The earliest documented slip on any of the faults (Picuris–Pecos, Nacimiento) is late Paleozoic. Lateral slip on north-striking faults in northern New Mexico during the late Mississippian–early Permian Ancestral Rocky Mountain orogeny was probably dextral and possibly of large magnitude. Laramide fault slip was also dextral and probably large (tens of km). The lateral slip component during the main phase of Rio Grande rifting (Miocene) was sinistral but of small magnitude. Lateral components during late rifting (latest Miocene–Holocene) are indeterminate, but small.

The 55–90 km net dextral separation on north-striking faults in northern New Mexico is probably the cumulative result of numerous tectonic events, not all of them dextral. If our analysis is correct, then the Ancestral Rocky Mountain and Laramide events are most likely responsible for the majority of the dextral separations seen today. The relative importance of dextral contributions by these two orogenies, however, has not yet been determined.

INTRODUCTION

Northern New Mexico is one of the few areas in the Southern Rocky Mountains where the anomalies in the regional aeromagnetic maps can be largely attributed to variations in the magnetic characteristics of Proterozoic basement rocks (Cordell and Keller, 1984, p. 21). In most other parts of the southern Rockies of New Mexico and Colorado the aeromagnetic anomaly pattern is complicated by Cenozoic intrusions, volcanic fields, and volcanic and volcaniclastic rocks preserved within rift basins. Non-volcanic parts of the Phanerozoic sedimentary succession, however, have relatively little aeromagnetic character and hence are largely transparent to high-altitude surveys. This is because the magnetic susceptibility of typical crystalline basement rocks is 5–35 times that of average sedimentary rocks (Telford et al., 1976, p.121). The regional aeromagnetic map of northern New Mexico (Plate 3) shows several dextral steps in anomalies that may be attributable to dextral separations of disparate Proterozoic basement lithotypes by north-striking faults. The best defined of these steps coincides with the Picuris–Pecos fault which has long been recognized as having accommodated about 37 km of net dextral separation of Proterozoic folds, ductile thrust faults, metasedimentary stratigraphies, and distinctive marker horizons (Miller et al., 1963; Grambling, 1979; Karlstrom and Daniel, 1993; Daniel et al., 1995). Because P–T conditions during peak metamorphism were similar on each side of the fault (~3.5 kbar, 510°C; Grambling, 1981; Daniel et al., 1995), the 37 km dextral separation on the fault must be largely the result of strike-slip. These geologic separations are reasonably matched by a similar dextral step (~42 km) in the aeromagnetic anomaly pattern (Plate 4; Daniel et al., 1995; V. J. S. Grauch, unpubl. aeromagnetic analysis, 2004). So, at least for the Picuris–Pecos fault, the dextral separation of aeromagnetic anomalies may be attributed mostly to strike-slip, although it should be emphasized that the present separation may be the cumulative result of multiple tectonic events with various slip directions.

The explanation for other dextral separations of aeromagnetic anomalies in northern New Mexico is less clear. Reconstruction of a Proterozoic orogenic belt in northern New Mexico and its associated aeromagnetic anomalies led Karlstrom and Daniel (1993) and Daniel et al. (1995) to invoke about 15 km dextral separation on the Tusas–Picuris fault, an inferred structure now largely buried within the Rio Grande rift. A similar reconstruction using only aeromagnetic data was recently compiled by V. J. S. Grauch (unpubl. map). The Nacimiento fault system (Plate 3) that bounds the western margin of both the Laramide Nacimiento uplift (Baltz, 1967) and the late Paleozoic Peñasco uplift (Woodward, 1996) has been interpreted to have accommodated significant dextral strike-slip. Geologically based slip estimates range from two kilometers to 20–33 km (Baltz, 1967; Woodward et al., 1992; Cather, 1999; Pollock et al., 2004; Cather, 2004). The Nacimiento fault is part of a larger system of strike-linked structures (Sand Hill fault, Salado–Cumbres structural discontinuity, Del Norte fault) that extends from southern Colorado to central New Mexico (Baltz, 1967; Brister and Chapin, 1994; Cather, 1999, 2004; see also the minipaper by Cather in the Day One roadlog). Aeromagnetic anomaly patterns associated with the Nacimiento fault and related structures can be interpreted either to support little strike-slip (Plate 3; Cordell and Keller, 1984) or about ~24 km of dextral separation (Plate 4). A few kilometers of dextral separation of mapped Proterozoic units appears to exist on the Borrego fault (Moench et al. 1988; Metcalf, 1995; Daniel, 1995), although the quantification of separation on this fault has not yet been adequately addressed. An additional ~5–10 km of dextral separation may be present on the frontal thrusts of the Sangre de Cristo Mountains (Plate 4), depending on if the slip on these faults was east-northeastward (e.g., Erslev et al., 2004; Magnani et al., 2005) or northeastward (Wawrzyniec et al., 2004).

In this paper we attempt to derive the slip history of the major north-striking faults in northern New Mexico that exhibit evidence for dextral strike separations, based on analysis of eight regional 1.4 Ga to Holocene tectonic events (Table 1). Because it is the best-exposed and best-studied of these faults, the slip history of the Picuris–Pecos fault will be emphasized. Our interpretations may also have applicability to other dextral structures in the region.

MAXIMUM AGE OF FAULTING

Dextral separations on the Picuris–Pecos and Tusas–Picuris faults are based largely on the reconstruction of a series of overturned folds, ductile faults, and marker beds within Paleoproterozoic rocks exposed in the Tusas, Picuris, Truchas, and Rio Mora ranges of northern New Mexico (Miller et al., 1963; Karlstrom and Daniel, 1993; Daniel et al., 1995). These structures involve, and are thus younger than, the 1.70–1.69 Ga Hondo Group (Karlstrom et al., 2004, p. 8). The folds and ductile faults have long been interpreted to have originated by north-south contraction during the 1.65 Ga Mazatzal orogeny (Williams, 1991; Karlstrom et al., 2004). This interpretation is supported by the dating of 1.67–1.68 Ga metamorphic rims on pre-1.70 Ga detrital monazite cores from the northern Tusas Mountains that are interpreted to date the initiation of thrusting (Kopera, 2003). There is also evidence for formation of new ductile fabrics and reactivation of older fabrics during major ductile deformation about 1.43–1.35 Ga. As examples: 1) the northernmost ductile thrust of the sequence of ductile structures used for piercing lines (Spring Creek shear zone of Davis, 2003) has granitic mylonites that yield zircon and monazite ages of 1.43 Ga and accommodated ~3 km of north-directed thrust offset of ~1.43 Ga isograds (Davis, 2003). 2) In the Picuris Mountains, 1.45 Ga metamorphic monazite inclusions are found within syn-S_3 porphyroblasts of garnet, cordierite, and andalusite (Wingsted, 1997; Williams et al., 1999). The dominant east-west subvertical ductile fabric in the range, S_3, formed at ~500º C and is now truncated by the Picuris–Pecos fault. Thus, movement on the Picuris–Pecos fault is younger than ~1.45 Ga.

Miller et al. (1963) described apparent ductile "drag" of bedding in metasedimentary rocks adjacent to the Picuris–Pecos fault, which they used to infer a probable Proterozoic origin for the dextral separation on the fault. Such folding of layered rocks, however, also occurs commonly in brittle deformational regimes (e.g., monoclines) where macroscopic "ductility" is achieved by brittle deformation acting on numerous slip planes, and thus does not require metamorphic conditions. Moreover, some workers have locally attributed the dextral deflection of contacts and foliations in the metasedimentary units near the Picuris–Pecos fault to brittle deformation mechanisms (McDonald and Nielsen, 2004, p. 225). Elsewhere along the fault, foliations in Proterozoic granite-gneiss show no systematic dextral deflection near the fault, but instead are commonly truncated by it at high angles (Booth, 1976; Moench et al., 1988; S. M. Cather and A. S. Read, unpublished mapping, 2004; K. E. Karlstrom, unpublished mapping, 2004).

REGIONAL TECTONIC EVENTS

To constrain the slip history of the Picuris–Pecos and related faults, we evaluate the regional kinematics of eight tectonic events from 1.4 Ga to Recent in the southwestern United States. In each case, we summarize existing data for the orientation of contractional and/or extensional deformations in the region. We then resolve the kinematic sense that these deformations might have had on north-striking faults in northern New Mexico to infer a potential lateral slip sense for each tectonic episode. The philosophy behind this analysis is that, where a preexisting fault or other plane of weakness exists in the crust, subsequent deformations may cause fault reactivation. The sense of slip during reactivation may be predicted from the resolved shear stress on the fault plane (i.e., the Wallace-Bott hypothesis), if stresses exceed the frictional strength of the fault (e.g., Angelier, 1994). In the Rocky Mountains, many workers have postulated that both Ancestral Rocky Mountains and Laramide faults represent such reactivation processes (Marshak et al., 2000; Timmons et al., 2001, Erslev et al., 2004). It is thus important to determine when faults formed for the first time (neoformed faults) versus when and how they may have been later reactivated. It cannot be demonstrated that all of the tectonic events described herein produced slip on the Picuris–Pecos or related faults in the area. Our objective is to infer the most probable sense, and possibly the magnitude, of lateral slip on these faults, *if* slip occurred. We also recognize that numerous minor tectonic events have affected northern New Mexico. It is unlikely, however, that these lesser events contributed in an important way to the observed major dextral separations.

~1.4 Ga Tectonism

Previously regarded primarily as an episode of widespread anorogenic magmatism, the 1.48–1.35 Ga period has become increasingly recognized as an episode of major tectonism and metamorphism in the southwestern U.S. (Nyman et al., 1994; Ralser, 2000; Williams et al., 1999; Karlstrom et al., 2004). Shortening directions were generally northwest or west-northwest (Nyman et al., 1994; Kirby et al., 1995; Karlstrom and Humphreys, 1998, fig. 2; Sims and Stein, 2003). Directly adjacent to the Picuris-Pecos fault east of Santa Fe, Melis (2001) documented ~1.48–1.37 Ga mylonitic foliation (S_2) that strikes east-northeast and records dextral strike-slip, consistent with regional evidence for west-northwest shortening. Such shortening orientations should produce left-lateral components of slip on north-striking faults such as the Picuris–Pecos (Fig. 1a). We emphasize, however, that no evidence exists to suggest the Picuris–Pecos fault had formed by ~1.4 Ga. Peak metamorphic conditions in north-central New Mexico were attained ~1.4 Ga (Williams et al., 1999; Karlstrom et al., 2004), with temperatures (500–550°C) and pressures (3.5–4.0 kbar) corresponding to mid-crustal depths (~12–15 km). Deformation under these conditions has produced zones (up to kilometers wide) of penetrative mylonitic foliations elsewhere in the Southwest (e.g., Karlstrom and Bowring, 1988; Shaw et al., 2001, 2005; McCoy et al., 2005; Karlstrom and Williams, in press). To date, however, no north-striking zones of mylonitic rocks have been reported anywhere along the Nacimiento or Picuris–Pecos faults. Although brittle slip events can take place during episodes of very high strain rates and high fluid pressures in the middle crust, these episodes occur within a longer-term regime of ductile creep. It is thus implausible that major middle-crustal slip along the Picuris–Pecos and Nacimiento faults would have taken place at these amphibolite-grade conditions without any record of associated ductile processes.

~1.1 Ga Grenville Deformation

The southwestern U.S. was affected by 1.3–1.0 Ga deformation, metamorphism, and magmatism related to the Grenville collisional orogeny along the southeastern margin of Laurentia. The effects of Grenville deformation varied with distance from the orogenic front. In Texas, crustal contraction and associated metamorphism was prevalent (Mosher, 1998; Bickford et al., 2000), giving way to a mix of far-field compression and extension in New Mexico and Arizona. The Grenville shortening direction in the Van Horn area of west Texas was north-northwest (Mosher, 1998; Bickford et al., 2000), and the extension direction during Grenville rifting and magmatism nearby in the Central Basin Platform region of southeastern New Mexico was east-northeast (Adams and Miller, 1995). An imprecisely dated, northwest-striking ~1.1 Ga dike in the Zuni Mountains of New Mexico (Strickland et al., 2003) is indicative of northeast-southwest extension. Northwest-striking dikes that fed ~1.1 Ga diabase sills in southern Arizona suggest northeast-southwest extension (Howard, 1991). In the Grand Canyon area of northwestern Arizona, early (~1.25 Ga) Grenville northwest-southeast shortening was followed by later (~1.1 Ga) northeast-southwest extension (Timmons et al., 2001; in press). In northern Colorado, the regionally extensive ~1.3 Ga Iron Dike strikes northwest (Wahlstrom, 1956; Braddock and Peterman, 1989), thus indicating the prevailing extension direction was northeast-southwest.

Regional Grenville kinematics thus suggest that the major north-striking faults of northern New Mexico, if they were either neoformed or reactivated at ~1.1 Ga, would have accommodated sinistral components of slip (Fig. 1b). The potential magnitude of such slip is unknown. There is no direct evidence that the Picuris–Pecos, Tusas–Picuris, or Nacimiento faults were active during Grenville deformation. However, thermochronologic data (Erslev et al., 2004) indicate one of the nearby range-bounding thrust faults on the eastern flank of the Sangre de Cristo Mountains, the north-striking Montezuma fault, was an active, contractile, east-down structure at ~1.0 Ga. Thermochronologic data (Erslev et al., 2004, fig. 4c) also suggest that prior to the beginning of differential uplift at ~1.0 Ga, basement rocks exposed in the southern Sangre de Cristo Mountains were at 200–350°C, corresponding to a probable paleodepth of ~8–12 km. Fault slip at such conditions should produce a preserved record of at least local mylonitic and ultramylonitic fabrics, and other evidence of deformation near the ductile-brittle transition. However, with the possible exception of the "drag" folds in layered metasedimentary rocks (Miller et al., 1963), no evidence for ductile deformation along the Picuris–Pecos fault has been noted.

Contrary to the interpretations of Fankhauser and Erslev (2004), detailed mapping at a scale of 1:6,000 as well as microscope and microprobe analysis by S. M. Cather, A. S. Read, and G. Rawling (unpubl. data) of brecciated Proterozoic granite-gneiss along the Picuris–Pecos fault at Deer Creek have revealed no mylonitic fabrics or other evidence of ductile deformation, other than what was inherited from the gneissic protolith. Indeed, except for a fault in the Joyita Hills near Socorro (Beck and Chapin, 1994) and the Fowler Pass fault (Andronicos and Carrick, 2003), no mylonitic precursor to any major Phanerozoic fault has been described in New Mexico. These relationships imply that the inception of most major Phanerozoic faults in New Mexico occurred in a brittle regime. Although the timing of cooling through the brittle-ductile transition may have varied between individual mountain ranges, the Proterozoic rocks of the Sangre de Cristo Mountains did not pass into the purely brittle regime (<200–250°C; Passchier and Trouw, 1996) until the Grenville episode or later (~1.2–0.8 Ga; Erslev et al., 2004, fig. 4c).

~0.8 Ga Rifting

From ~1.1 Ga to ~0.6 Ga, western North America underwent a prolonged period of rifting that ultimately led to the establishment of a passive margin (the Cordilleran miogeosyncline) in the western U.S. by Cambrian time. East-west extension produced north-striking normal faults in the Grand Canyon region (Timmons et al., 2001) and may have initiated much of the north-south structural grain throughout Rocky Mountain–Colorado Plateau region (Karlstrom and Humphreys, 1998; Marshak et al., 2000; Timmons et al., 2001). Such east-west extension would not impart significant lateral components to the north-striking faults of northern New Mexico.

Development of the Neoproterozoic Uinta aulacogen (or intracratonic rift; Condie et al., 2001) to the north of what is now the Colorado Plateau implies north-south extension occurred in

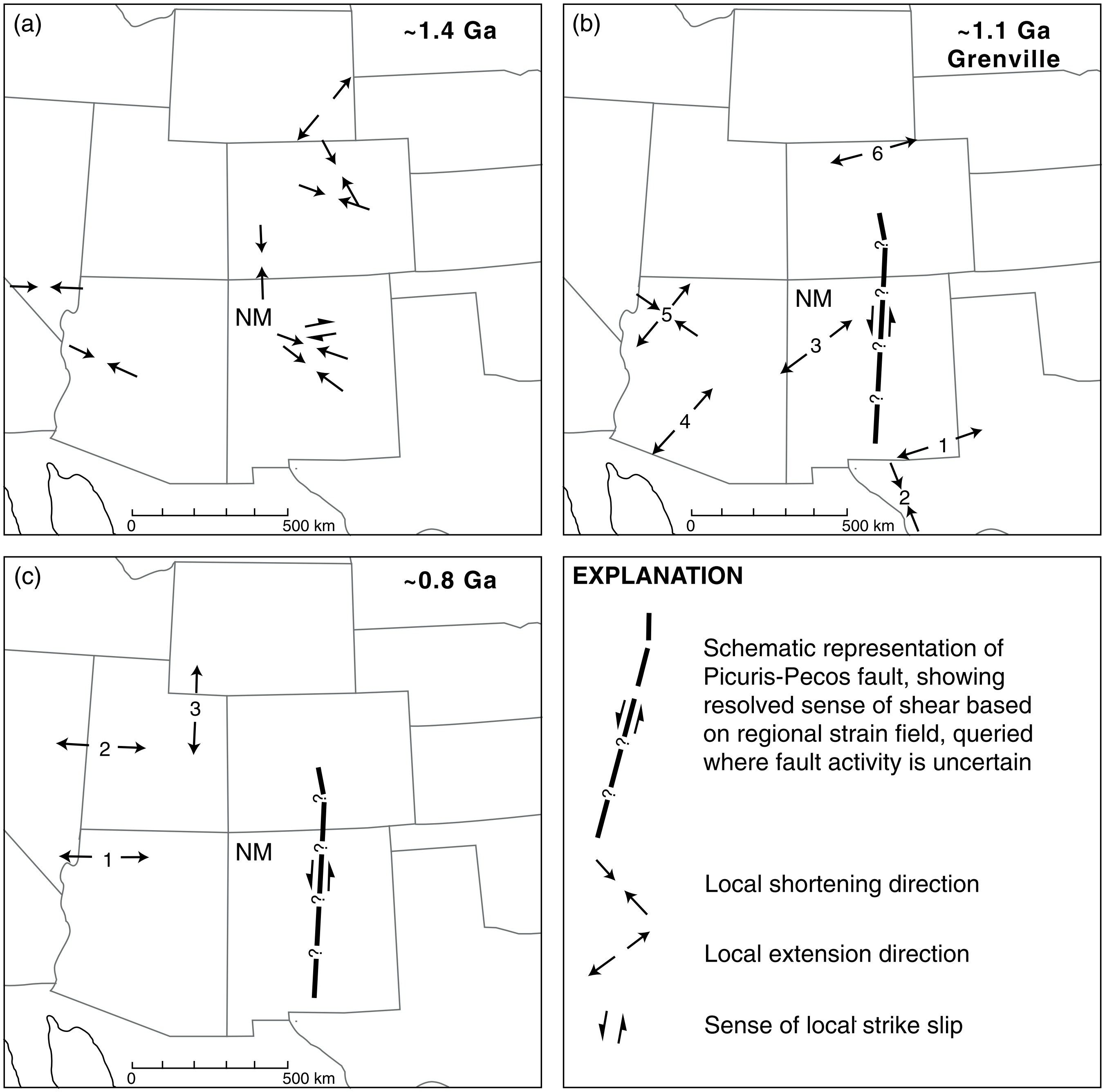

FIGURE 1. Map showing horizontal shortening and extension directions during Proterozoic deformations in the southwestern U.S. and resolved shear senses on north-striking faults in northern New Mexico. Note that for simplicity only the Picuris–Pecos fault is shown. See text for discussion. **(a)** ~1.4 Ga shortening and extension directions (Karlstrom and Humphreys, 1998, fig. 2) and dextral shear (1.48–1.37 Ga) on east-northeast-striking mylonitic foliation in north-central New Mexico (Melis, 2001). Note that the Picuris–Pecos and related faults were not in existence at this time. **(b)** ~1.1 Ga Grenville deformation. **1**. Extension direction during ~1.1 Ga rifting in Central Basin Platform area (Adams and Miller, 1995). **2**. ~1.2 Ga contraction direction near Van Horn, Texas. (Mosher, 1998; Bickford et al., 2000). **3**.Extension direction for ~1.1 Ga dike in Zuni Mountains (Strickland et al., 2003). **4**. Generalized extension direction from ~1.1 Ga feeder dikes in southern Arizona (Howard, 1991). **5**. ~1.25 Ga northwest-southeast shortening inferred from synsedimentary, northeast-trending monoclines, followed by ~1.1 Ga northeast-southwest extension determined from northwest-striking normal faults in the Grand Canyon region (Timmons et al., 2001; in press). **6**. Extension direction for ~1.3 Ga Iron Dike of northern Colorado (Wahlstrom 1966, Braddock and Peterman, 1989). **(c)** ~0.8 Ga extension. **1**. East-west extension in the Grand Canyon area (Timmons et al., 2001). **2**. Generalized east-west extension direction during rifting of Rodinia (Karlstrom and Humphreys, 1998). **3**. North-south extension in Uinta aulacogen (Condie et al., 2001).

that area (Fig. 1c). If this extension caused southward relative motion of the proto-Colorado Plateau block, and if such motion were accommodated by north-striking faults in northern New Mexico, then the predicted sense of slip on these faults would be sinistral. The magnitude of slip needed to accommodate extension in the Uinta aulacogen probably would not be large (kilometers, not tens of kilometers). Although late Proterozoic activity along the Nacimiento, Tusas–Picuris, or Picuris–Pecos fault has yet to be demonstrated, thermochronologic data indicate the nearby, north-striking Montezuma fault was reactivated ~0.7 Ga as a west-down extensional structure (Erslev et al., 2004).

Cambrian (~530 Ma) Extension in the Southern Oklahoma Aulacogen

The southern Oklahoma aulacogen formed as a failed arm during late Proterozoic–early Cambrian rifting of southeastern North America. The aulacogen trends west-northwest and is a deeply subsided trough that is filled with a bimodal suite of extrusive and intrusive igneous rocks that accumulated ~535–530 Ma (Keller and Baldridge, 1995; Hogan and Gilbert, 1997). The aulacogen was subsequently structurally inverted and partially stripped by erosion during late Paleozoic transpressional tectonism. The preserved aulacogen fill extends west-northwestward into, or near, the Texas panhandle. Sparse igneous stocks and west-northwest-striking dikes of Cambrian age may mark its intrusive underpinnings in southern Colorado and northern New Mexico (Larson et al., 1985). Alternatively, these sparsely distributed intrusive rocks may be part of a Cambro–Ordovician (574–427 Ma) magmatic suite that is broadly distributed throughout New Mexico and southern Colorado (i.e., the north to north-northeast-trending New Mexico aulacogen of McMillan and McLemore, 2004.)

The present west-northwestward extent of the southern Oklahoma aulacogen has been partly determined by the extent of late Paleozoic tectonic inversion and erosion. For example, the Pennsylvanian Apishapa uplift of southeastern Colorado, presently underlain by Proterozoic granite, lies approximately on-trend with the southern Oklahoma aulacogen. If the bounding structures of the Apishipa uplift reactivated (i.e., inverted) the western part of the aulacogen (Larson et al., 1985, p. 1371), then it is possible that Cambrian rifting extended west-northwest and terminated near the Rocky Mountain front. If such crustal extension were accommodated by the relative southward motion of the Texas–eastern New Mexico block, then north-striking faults in northern New Mexico may have experienced dextral slip during the Cambrian (Fig. 2a). The magnitude of dextral slip necessary to accommodate such extension is not large (probably a few km, not tens of km).

Late Paleozoic (~325–290 Ma) Ancestral Rockies Orogeny

In late Mississippian, Pennsylvanian, and early Permian time, southwestern and south-central North America was strongly deformed by the Ancestral Rocky Mountain orogeny. The sense of slip of major faults in the region is poorly constrained except in a few localities. In Colorado and Oklahoma, the principal fault fabric strikes northwest or west-northwest. On some uplifts, major bounding thrust faults that face north-northeast (Wichita uplift), or southwest (Uncompahgre uplift) have been documented (Brewer et al., 1983; Frahme and Vaughn, 1983), and substantial left-lateral slip has been proposed (Budnik, 1986). In parts of south-central Colorado and central New Mexico, the dominant late Paleozoic structural trends were north-south (e.g., Broadhead, 2001a,b,c). Faults of this orientation tended to be steep and modestly contractile, although at least one clear example of a north-striking normal fault of late Pennsylvanian age has been documented (Beck and Chapin, 1994). This latter fault, beautifully exposed in the Joyita Hills area of central New Mexico, also shows excellent slickenline evidence for a modest sinistral component of slip. Most other indicators of lateral slip (they are few) on north-striking Pennsylvanian faults in New Mexico and southern Colorado, however, are dextral. These include evidence for dextral shear on the north-northwest-striking bounding faults of the Central Basin Platform in southeastern New Mexico (Yang and Dorobek, 1995), minor-fault arrays and northwest-trending en echelon folds near Alamogordo, New Mexico (Otte, 1959; Cather, 2000; Howell et al., 2002), north-northwest trending en echelon basins and uplifts east of the Picuris-Pecos fault (Baltz and Myers, 1999) and northwest-trending, en echelon growth-folds in Pennsylvanian–Permian deposits adjacent to the Pleasant Valley fault near Salida, Colorado (Wallace et al., 2000).

Although contradictions exist locally and more work is clearly needed, a dominance of dextral components of slip on north-striking faults, probable left slip on some west-northwest-striking faults, and major contractile structures that face southwest or north-northeast favor a tectonic model that involves northeast-southwest crustal shortening. Ye et al. (1996) proposed such a model, although it should be emphasized that parts of their Laramide-style model are questionable (such as the apparent lack of subduction-related magmatism). Competing models involving northwest-southeast shortening (e.g., Kluth and Coney, 1981) may yet prove to have local or temporal applicability.

If the kinematics of Ancestral Rocky Mountain deformation were dominated by northeast-southwest contraction, then north-striking faults in northern New Mexico potentially slipped in a dextral sense at that time (Fig. 2b). Stratigraphic data indicate Pennsylvanian dip-separation occurred on the Nacimiento fault (Woodward, 1996) and the Picuris–Pecos fault (Miller et al., 1963; Casey, 1980; Soegaard, 1990; Soegaard and Caldwell, 1990). Baltz and Myers (1999) also interpreted Pennsylvanian dextral components for the Picuris-Pecos fault. Tectonic breccia along the Picuris–Pecos fault locally contains fracture- and fissure-fills of Mississippian carbonate (Fankhauser and Erslev, 2004) that indicate brittle deformation on the fault occurred prior to and during the late Mississippian. Because of the complexity of the Ancestral Rockies orogen and the relative scarcity of kinematic data, it is not possible to deduce the magnitude of dextral slip from regional structural-balancing considerations. Pennsylvanian dextral-slip components on north-striking faults in northern New Mexico therefore are possibly, but not demonstrably, large (cf. Woodward et al., 1999).

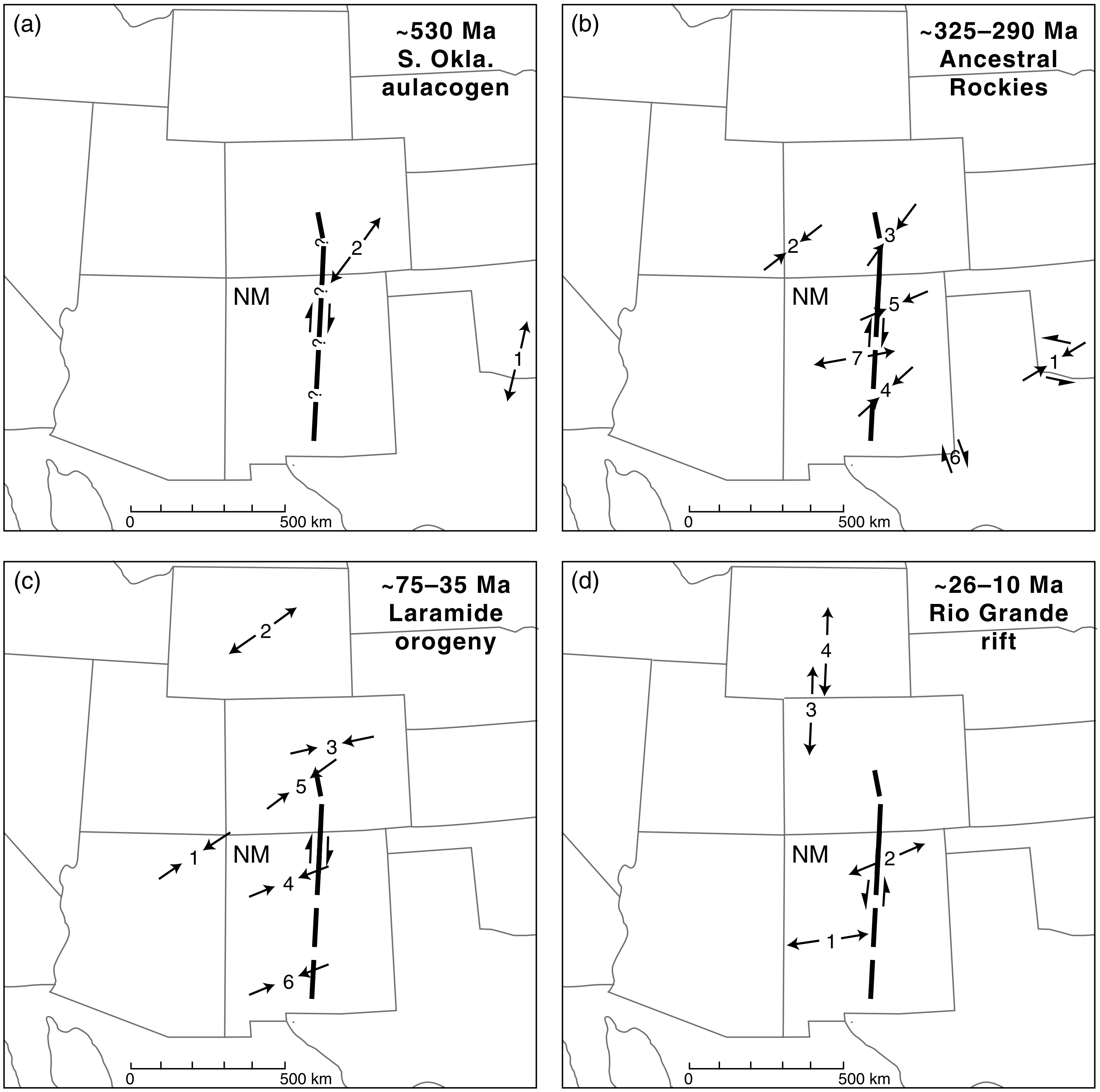

FIGURE 2. Maps showing distribution of contraction and extension directions for Phanerozoic tectonic events in the southwestern U.S. and resolved shear stress on north-striking faults in northern New Mexico. For simplicity, only the Picuris–Pecos fault is depicted. See text for discussion. Symbols are explained in Figure 1. **(a)** Cambrian extension during opening of the southern Oklahoma aulacogen. **1**. Extension direction in southern Oklahoma aulacogen (Keller and Baldridge, 1995). **2**. Extension direction in the hypothetical westward continuation of the aulacogen in the Apishipa uplift area of southeastern Colorado (Larson et al., 1985). **(b)** Late Mississippian, Pennsylvanian, and early Permian Ancestral Rocky Mountain orogeny. **1**. Directions of major crustal shortening and probable sinistral deformation in the Wichita uplift area (Brewer et al., 1983; Budnik, 1986). **2**. Direction of major crustal shortening in the Uncompahgre uplift (Frahme and Vaughn, 1983). **3**. Shortening direction for northwest-trending en echelon folds adjacent to the Pleasant Valley fault (Wallace et al., 2000). **4**. Shortening direction for en echelon folds adjacent to the Fresnal fault (Otte, 1959). **5**. Approximate shortening direction for en echelon basins and uplifts in the southern Sangre de Cristo Mountains (Baltz and Myers, 1999, fig. 71). **6**. Dextral deformation in the Central Basin Platform area (Yang and Dorobek, 1995). *7*. Approximate extension direction for striated late Pennsylvanian fault, Joyita Hills (Beck and Chapin, 1994; note that this extension direction is at odds with the other kinematic indicators in this figure). **(c)** Late Cretaceous–Eocene Laramide orogeny. **1**. Contraction direction from dominant trend of folds in the central Colorado Plateau (Kelley, 1955; Woodward, 1984). **2**. Contraction direction from dominant trends of basins and uplifts, central Wyoming (Brown, 1993, figs. 3, 4). **3**. Generalized shortening direction from minor-fault data, Front Range (Erslev et al., 2004). **4**. Shortening direction for en echelon folds in eastern San Juan Basin (Baltz, 1967). **5**. Generalized shortening direction from minor-fault data in central Colorado (Wawrzyniec et al., 2002). **6**. Generalized shortening direction in southwestern New Mexico (Seager, 2004).

Late Cretaceous–Eocene (~75–35 Ma) Laramide Orogeny

The Laramide orogeny in New Mexico and southern Colorado has been extensively reviewed in the recent literature (Cather, 2004), therefore only those aspects pertinent to the present analysis will be described herein. Laramide deformation involved regional northeast or east-northeast crustal shortening, as shown by numerous criteria including the dominant northwest trend of contractile structures in Wyoming and on the central Colorado Plateau (Kelley, 1955; Hamilton, 1981, 1988; Chapin and Cather, 1981; Brown, 1993), minor-fault arrays in the southern Rocky Mountains (Erslev, 2001; Wawrzyniec et al., 2002; Erslev et al., 2004), and joint patterns (e.g., Lorenz and Cooper, 2003). Laramide northeast-southwest shortening is compatible with dextral components of slip on reactivated north-striking faults in northern New Mexico (Fig. 2c). Evidence for such slip has been described along the Nacimiento fault (Baltz, 1967; Woodward et al., 1992; Cather, 1999; Pollock et al., 2004). Laramide dextral slip on the Picuris–Pecos fault has also been inferred by many workers (Chapin and Cather, 1981; Karlstrom and Daniel, 1993; Daniel et al., 1995; Bauer and Ralser, 1995; Cather, 1999).

The only definitive evidence for Laramide strike-slip yet documented on a part of the Picuris–Pecos fault system (the Glorieta Mesa–Estancia Basin fault of Cather, 1999) is the mismatched Upper Cretaceous Dakota Sandstone stratigraphy across strands of the fault that requires substantial (at least several km) of post-Dakota Sandstone, pre-27 Ma dextral strike juxtaposition (Cather and Lucas, 2004). In contrast, Fankhauser and Erslev (2004) correlated limestone beds and mapped a small fault across the Picuris–Pecos fault at Deer Creek (~18 km southeast of Santa Fe), and argued that these relationships may prohibit major post-Paleozoic dip-slip or strike-slip on the fault. Stratigraphic analysis by A. S. Read, D. Ulmer–Scholle, and S. M. Cather (in Erslev et al., 2004, p. 29-30), however, has shown the limestone correlation depicted by Fankhauser and Erslev (2004, the queried correlation in their fig. 8) is a miscorrelation between the Mississippian Terrero Formation on the west with the middle or upper part of the Pennsylvanian Madera Group on the east, a relationship that indicates a major strand of the Picuris–Pecos fault lies beneath Deer Creek with possibly hundreds of meters of east-down stratigraphic separation. Moreover, unpublished geologic mapping at 1:6,000 scale by S. M. Cather and A. S. Read indicates that the northwest-striking "keel" fault cannot be traced to the east side of Deer Creek as depicted by Fankhauser and Erslev (2004, fig. 2) and thus does not pin the Picuris–Pecos fault.

Most recent tectonic models for the Laramide of northern New Mexico invoke dextral components of slip along the eastern margin of the Colorado Plateau, with slip accommodated on a family of north-striking structures. Estimates of the magnitude of dextral slip vary markedly (see review by Cather, 2004). Perhaps the most robust argument that significant dextral slip of Laramide age occurred in the southern Rockies is the need to structurally balance large amounts of crustal shortening north of the Colorado Plateau with the more modest shortening along its eastern margin. This obvious balancing requirement was the basis for some of the early papers that invoked substantial dextral slip in the southern Rockies (Chapin and Cather, 1981; Hamilton, 1981) but has rarely been addressed by some of the later critics of the concept. While we acknowledge the ongoing controversy, these balancing requirements seemingly cannot be met without invoking large (tens of km) Laramide dextral slip in northern New Mexico. Dextral transpression in New Mexico may have been accommodated by a partitioned slip system of discrete strike-slip and dip-slip faults (Cather, 2004; Cather and Lucas, 2004), but likely gave way northward to a weakly partitioned system of dextral oblique faults in Colorado, much like that envisioned by Wawrzyniec et al. (2002) and by S. M. Cather and C. E. Chapin (ongoing mapping and structural analysis in Colorado).

Main Phase (Miocene, ~26–10 Ma) of the Rio Grande Rift

Incipient extension in the Rio Grande rift began ~36–35 Ma (Cather, 1990; Mack et al., 1994), but basins generally did not begin accumulating sediments until ~26 Ma (Chapin and Seager, 1975; Chapin and Cather, 1994). The kinematics of extension during this early phase of rifting are poorly known.

The Miocene (principally the middle to late Miocene) saw the main phase of subsidence and sedimentation in the Rio Grande rift. Sinistral oblique deformation related to northeast-southwest extension occurred in the Rio Grande rift at this time as shown by several lines of evidence.

(1) Rift-related basins, including the Browns Park Basin and the Split Rock Basin, formed north of the Colorado Plateau by north-south extension and accumulated Miocene continental deposits (Chapin and Cather, 1994, p. 8). These extensional basins require that the plateau had a southward component of motion relative to cratonic North America, thus imparting sinistral components to the Rio Grande rift.

(2) Late Oligocene to late Miocene igneous dikes are variably oriented near the rift, presumably due to the effects of preexisting faults and other inhomogeneities. Dikes that intruded relatively isotropic Oligocene stocks near Socorro and Questa, however, strike northwest and are thus indicative of northeast-southwest extension (Aldrich et al., 1986, p. 6207).

(3) Transfer faults that link half grabens of opposing tilt polarity, such as the northeast-striking Embudo fault, are typically subparallel to the extension direction (Faulds and Varga, 1998).

(4) The presence of northwest-trending early rift basins near Albuquerque (Hudson et al., 2001) are suggestive of northeast-southwest extension.

FIGURE 2. (continued) **(d)** Miocene extension in the Rio Grande rift. **1**. Generalized extension direction from several late Oligocene–early Miocene dikes west of Socorro (Aldrich et al., 1986). **2**. Extension direction from early Miocene dikes in the Questa caldera area (Aldrich et al., 1986). **3**. Extension direction in Browns Park (1984, 1986). **4**. Extension direction in Split Rock Basin, Granite Mountains area (Love, 1970; Chapin and Cather, 1994).

(5) Most paleomagnetic rotation data for post-Laramide rocks in New Mexico are anticlockwise (Brown and Golombek, 1985, 1986; Salyards et al., 1994; Hudson et al., 2004; Harlan and Geissman, 2004). These data are most reasonably interpreted as having resulted from sinistral components of slip in the rift. In the Española Basin, Wawrzyniec et al. (2002) argued that anticlockwise rotations of highly elongate fault blocks may have occurred in response to dextral oblique extension. Such fault-block geometries, however, have not been documented in the Española Basin.

Wawrzyniec et al. (2002) interpreted that west-northwest extension caused dextral components of slip in the Rio Grande rift, based on minor-fault arrays from six localities in Colorado. This interpretation requires northward components of relative motion of the Colorado Plateau, but is seemingly at odds with several aspects of the regional geology. During the preceding Laramide orogeny, contractile deformation in the Uinta uplift accommodated part of the northeast-southwest convergence between the Colorado Plateau and the Wyoming craton. Following the cessation of Laramide tectonism, the range-bounding thrusts of the Uinta uplift became inactive and were beveled by the Gilbert Peak erosion surface and then mantled by the Bishop Conglomerate (Hansen, 1984, 1986). These thrust faults have thus seen little or no contractile reactivation since deposition of the Bishop Conglomerate, which contains early Oligocene ash beds (Balls et al., 2004). These relationships suggest that northward components of relative Plateau motion have not been renewed since the end of the Laramide.

In the Miocene, inversion of several Laramide structures (including the eastern Uinta uplift at Browns Park) began north of the Plateau during north-south extension (Chapin and Cather, 1994), a kinematic constraint that is incompatible with the dextral-oblique rift extension model of Wawrzyniec et al. (2002). Although we have no ready explanation for the minor fault data of Wawrzyniec et al. (2002), we note that several other localities in Colorado have yielded minor-fault arrays in post-Laramide rocks that are compatible with sinistral-oblique rifting (E. A. Erslev, oral commun., 2001; C. E. Chapin and S. M. Cather, unpubl. data). From these relationships we infer that Miocene extension in the Rio Grande rift was sinistral-oblique (Fig. 2d). Based on the magnitude of Miocene extension north of the Colorado Plateau, the sinistral component was not large (a few km, not tens of km).

Parts of the Picuris–Pecos fault were clearly active during Miocene rifting, but perhaps mainly as dip-slip structures. These include the northern extension of the Picuris–Pecos fault where it forms the eastern boundary of the San Luis Basin (the Sangre de Cristo fault; Brister and Gries, 1994), and the Jarilla fault of the Tularosa Basin (Cather and Harrison, 2002). South of Lamy, New Mexico, the 27 Ma Galisteo dike effectively pins part of the Picuris–Pecos fault system (Lisenbee, 2000; Cather and Lucas, 2004) and requires that no major lateral slip occurred there since the late Oligocene. The Sand Hill fault, the southward extension of the Nacimiento fault, was also probably active in the Miocene, but lateral components of slip, if any, are poorly understood.

Late Phase (latest Miocene–Holocene, ~10–0 Ma) of the Rio Grande Rift

The sense of obliquity is not well constrained for the younger phase of rift extension. Cessation of sedimentation in extensional basins north of the Colorado Plateau in the late Miocene (Chapin and Cather, 1994) implies either a cessation of southward components of relative plateau motion or that regional degradation began to exceed extensional subsidence and accommodation at that time. Geologic evidence suggests dextral components of slip related to Plio–Pleistocene extension in the Santo Domingo Basin (Karlstrom et al., 1999, p. 163; Chamberlin, 1999). In the nearby Española Basin, however, anticlockwise paleomagnetic rotations (Hudson et al., 2004) may imply post-2.5 Ma sinistral slip. Menges (1990) also inferred sinistral slip components for the Sangre de Cristo fault in northern New Mexico. Thus, although no clear sense of obliquity can be attributed to late rift extension, the relatively modest rates of deformation that characterize younger rifting (Chapin and Cather, 1994) imply that strike-slip components were of small magnitude at most.

DISCUSSION

North-striking faults in northern New Mexico exhibit net dextral separations of ~55–90 km. These separations are best exemplified by the Picuris–Pecos fault and may be the cumulative result of numerous slip events, not all of them dextral. Initial development of the Picuris–Pecos fault was post ~1.45 Ga and probably no older than ~1.2–0.8 Ga, as shown by the lack of ductile precursors.

Our analysis suggests that the only deformations known in northern New Mexico that could have produced large dextral separations are the late Paleozoic Ancestral Rocky Mountain orogeny and the Late Cretaceous–Eocene Laramide orogeny. All other major tectonic events were either sinistral or potentially produced only relatively minor dextral components (Table 1). Our analysis is consistent with the results of Cather and Harrison (2002) who interpreted ~70 km of post-Devonian (Ancestral Rocky Mountain and Laramide) net dextral slip in southern New Mexico, based on dextral separations of lower Paleozoic isopach contours. The relative importance of Ancestral Rocky Mountain vs. Laramide contributions to the dextral slip history of faults in New Mexico is an important research target, and may prove to be difficult to determine.

ACKNOWLEDGMENTS

The senior author acknowledges field and logistical support from the New Mexico Bureau of Geology and Mineral Resources (Dr. P.A. Scholle, Director). Lynne Hemenway typed the manuscript and Leo Gabaldon drafted Figures 1 and 2. Martha Cather and Mark Mansell constructed Plates 3 and 4. We benefited from discussions with Chuck Chapin, Eric Erslev, Seth Fankhauser, Tien Grauch, Matt Heizler, Randy Keller, Geoff Rawling, Adam Read, Rob Sanders, Dana Ulmer-Scholle, and Tim Wawrzyniec. The manuscript was improved by reviews from Chuck Chapin,

TABLE 1. Summary of fault activity, lateral slip sense and lateral slip magnitude for major north-striking faults that exhibit dextral separations in northern New Mexico during major 1.4 Ga to Holocene tectonic events.

Tectonic event	Fault activity	Lateral slip sense	Lateral slip magnitude (small = a few km; large = 10s of km)
Latest Miocene to Holocene Rio Grande rifting (~10–0 Ma)	Local	Indeterminate	Small
Miocene main phase of Rio Grande rifting (~26–10 Ma)	Local	Sinistral	Small
Laramide orogeny (~75–35 Ma)	Yes	Dextral	Probably large
Ancestral Rocky Mountain orogeny (~325–290 Ma)	Yes	Probably dextral	Possibly large
Cambrian rifting (~530 Ma)	?	Dextral	Small
~0.8 Ga extension	?	Sinistral	Small
~1.1 Ga Grenville orogeny	?	Sinistral	?
~1.4 Ga metamorphism and deformation	No	Potentially sinistral	?

Matt Heizler, Randy Keller, Adam Read, and an anonymous reviewer.

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PLATE 1: LANDSAT ETM+ IMAGE – CHAMA BASIN AND SURROUNDING AREA

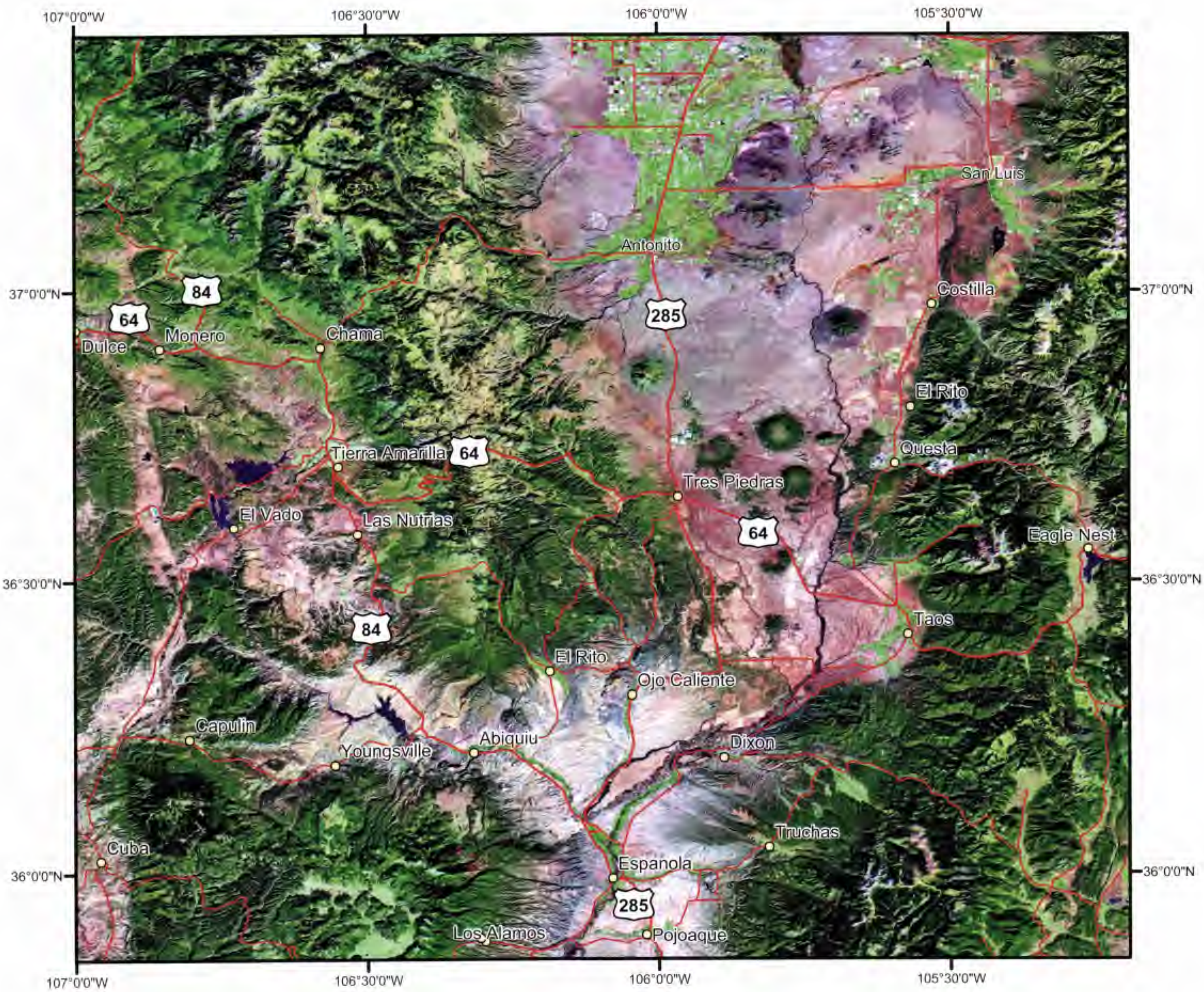

PLATE 1. LANDSAT 7 ETM+ image of the Chama Basin and southern San Luis Basin from two scenes acquired 14-Oct-1999. Image processing by Sawyer et al. (2004). Band 7-4-2 (RGB) panchromatically sharpened with 15-meter Band 8 data.