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Karl E. Karlstrom, S. M. Cather, M. T. Heizler, F. J. Pazzaglia, and M. Roy

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SANDIA MOUNTAINS AND RIO GRANDE RIFT: ANCESTRY OF STRUCTURES AND HISTORY OF DEFORMATION

K. E. KARLSTROM[1], S. M. CATHER[2], S. A. KELLEY[2], M. T. HEIZLER[2], F. J. PAZZAGLIA[1], and M. ROY[1]
[1]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131; [2]New Mexico Bureau of Mines and Mineral Resources, 801 Leroy Place, Socorro, NM 87801

Abstract—The Sandia Mountains and other rift flanks of the Rio Grande rift are, in large part, the product of both Laramide contraction and Neogene extension superimposed upon an already segmented crust. Rio Grande rift extension represents tectonic inversion (extensional collapse) of Laramide Rocky Mountain structures. Laramide structures were strongly influenced by older NE (1.65 and 1.4 Ga), NW (1.1 Ga), and N–S (0.8 Ga) structural grains.The Sandia Mountain area is important for interpretation of the relative importance of Laramide versus Miocene structures. Reverse faults along the eastern flank of the mountains suggest the Sandia Mountians were a northern extension of the Montosa uplift that resembled a mirror image of the Nacimiento uplift. However, apatite fission-track data indicate that cooling of Proterozoic basement through 60–120° C did not take place until after 30 Ma. Hence, we infer a mildly positive Laramide uplift (hundreds of meters, not kilometers, of structural relief). Normal faulting in the Placitas fault system, at the northern end of the Sandias, began during Laramide time in a releasing bend step between the dextral Rincon and San Francisco faults. Neogene uplift of the Sandia footwall due to tectonic denudation on these faults resulted in northward tilting of beds at the northern end of the Sandias and increase in dips of normal faults of the Placitas fault system. Our interpretation suggests a multistage uplift history for the Sandia Mountain block.

INTRODUCTION

The Sandia Mountains form part of the eastern flank of the Rio Grande rift, a zone of crustal extension that subparallels the Rocky Mountains from northern Colorado to Texas, and forms a narrow extensional trough in northern New Mexico (Chapin and Cather, 1994). The present structural and physiographic expression of the Sandia Mountains and the Rio Grande rift are the product of continental extensional tectonism that took place mainly since the beginning of the Miocene. However, like the adjacent Rocky Mountain uplifts and the Colorado Plateau, the Sandia Mountains record a long history of tectonism (Kelley, 1977). As suggested by Baars (1982), "perhaps the mystery of the location and significance of the rift will be resolved by the understanding of basement tectonics rather than by surface structure." In this paper, we examine the Precambrian ancestry of structures and the importance of Laramide contractional and strike-slip structures on the present form of the Sandia Mountains.

Methods for examining ancestry of structures have evolved considerably in the last few decades because of better understanding (and dating) of the tectonic events in the Southwest, and new structural tools for understanding the segmented geometry and kinematic framework that operate in active fault systems (Scholtz; 1990; Angelier, 1994). There have been several recent, small-scale kinematic studies in the Sandias (Abbott and Goodwin, 1995; Erslev, 1998), but there is continued difficulty in dating fault movement(s). This paper takes a regional approach and applies well-established (but still debatable) concepts to understand the development of fault systems during different tectonic events. First, the widely used "lineament" approach to understanding basement structures (Mayo, 1958; Baars, 1982; Marshak and Paulson, 1996) remains valid, if used with caution. Our approach here is to examine the regional tectonic history to decide during which event a given fault system is most likely to have originated. Second, based on theoretical studies and numerous well-documented examples (e.g., of Laramide high angle faults: Huntoon, 1990), we assume that, once established, fault systems may continue to influence deformation if stress fields are in favorable orientations. We view the upper crust as pervasively cracked and segmented at many scales.

We use the term "reactivation" in a very general sense to mean that older crustal anisotropy has influenced the orientation of a given deformational fabric or fault zone. This can be a simple mechanical reactivation along an interface (i.e., frictional sliding on older zones of mechanical weakness). In particular, major crustal boundaries at deep crustal levels might create major lineaments that are continually reactivated during later tectonism. Alternatively, following Karlstrom and Humphreys (1998), "volumetric" inheritance may occur in which a distinctive compositional character of a given segment of the crust may influence its deformational or magmatic response to later tectonism.

To identify Laramide structures in the Sandia Mountains, we interpret regional evidence to indicate that Laramide structures formed during an episode of ENE–NNE crustal shortening and involved reactivation of still older structures. In the adjacent Colorado Plateau the most common features of Laramide deformation are monoclinal uplifts that are commonly cored by high-angle reverse faults. High-angle reverse faults are incompatible with the Andersonian theory of faulting and are themselves usually interpreted to be an indication of frictional slip on older high-angle faults induced by Laramide subhorizontal compression. Many Rocky Mountain uplifts began as monoclines and then were cut by thrust or reverse faults as deformation proceeded (Berg, 1962). In New Mexico, many of these faults (Tijeras-Cañoncito, Picuris-Pecos, Sand Hill-Nacimiento, Hot Springs-Walnut Canyon) may have undergone Laramide dextral strike slip (Cather, in press). Estimates of the magnitude of dextral strike slip range between 5–20 km (Woodward et al., 1997), 60–120 km (Chapin and Cather, 1981), 33–110 km (Cather, in press), and 100–170 km (Karlstrom and Daniel, 1993).

It has long been recognized in the Grand Canyon that Laramide monoclines reactivated Proterozoic faults systems (Walcott, 1889). Recent work by Timmons et al. (in prep.) shows that Laramide monoclines follow older master faults that formed during at least two Proterozoic extensional events. An event at about 1.1 Ga produced NW-striking extensional faults and was apparently related to NW intracratonic shortening in front of the Grenville collision. A second event produced N–S normal faults during deposition of the Neoproterozoic Chuar Group (about 800 Ma). Both sets of normal faults were inverted during Laramide contraction so that graben systems became horst-shaped uplifts, and the bounding faults were reactivated and became the nucleus of monoclines. Timmons et al. (in prep.) propose that these structures were regional in scale and perhaps also affected New Mexico; this idea is further developed below.

PRE-LARAMIDE ANCESTRY OF STRUCTURES

Foliation trajectories for Paleoproterozoic rocks (1.8–1.6 Ga) in New Mexico are complex (Fig. 1) and often involve interference patterns attributed to multiple deformations. Foliation patterns probably vary with depth (Karlstrom and Williams, 1998), and dramatic changes in foliation are documented adjacent to syntectonic plutons (Read et al., 1999). Nevertheless, there is an overall northeast strike of dominant foliations, major shear zones, and province boundaries that reflects the

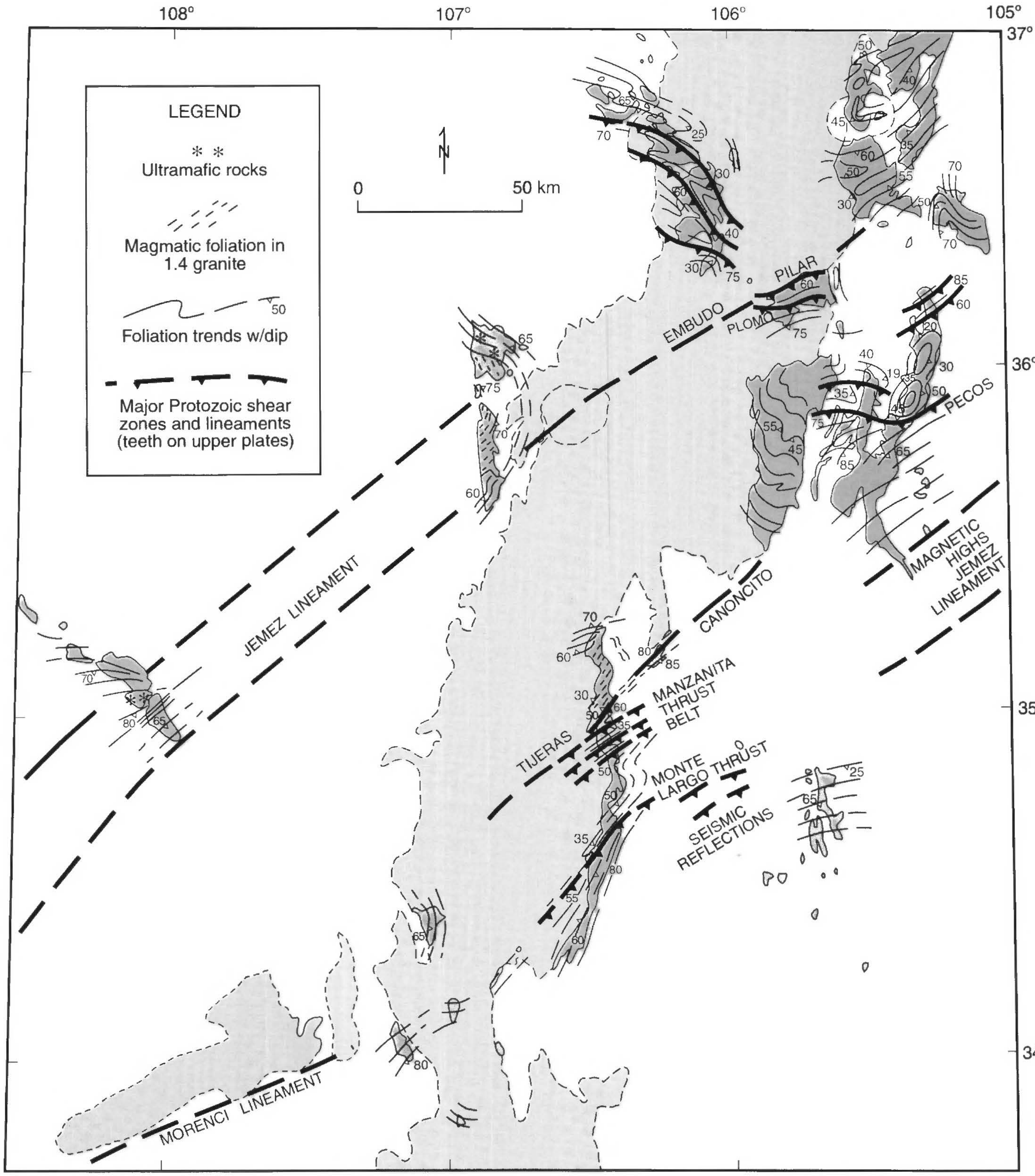

FIGURE 1. Proterozoic foliations in New Mexico and other Proterozoic structural "grain." Dark pattern is exposure area of Proterozoic rocks; light pattern represents basins of the Rio Grande rift.

dominance of NW–SE contractional assembly of the continental lithosphere ca. 1.7–1.65 Ga (Karlstrom and Bowring, 1993), followed by renewed NW–SE contractional deformation at ca. 1.4 Ga (Nyman et al., 1994). Major geophysical lineaments also suggest a deep-seated NE-striking fabric, in particular the Jemez lineament (Mayo, 1958; Aldrich et al., 1985) and Morenci lineament (Mayo, 1958; Chapin et al., 1978). The Jemez lineament corresponds approximately with the southern margin of >1.7-Ga basement of the Yavapai province (Karlstrom and Humphreys, 1998) and is inferred to be a major Proterozoic province boundary.

In the vicinity of the Sandia Mountains, several northeast-striking transfer zones in the Rio Grande rift have also been inferred to reflect pre-rift inheritance, possibly of NE-striking subvertical Proterozoic foliation (Kelley and Northrop, 1975; Chapin and Cather, 1994). Perhaps the best exposed transfer zone is the NE-striking subvertical Tijeras-Cañoncito fault system of the southern Sandia Mountains (Lisenbee at al., 1979). In Tijeras Canyon, the subvertical brittle Tijeras fault crosscuts Proterozoic foliation of similar strike but shallower dip (Fig. 1; Karlstrom et al., 1994; Abbott, 1997). Here, NE grain was not simply inherited by mechanical reactivation of Paleoproterozoic foliations, at least at these crustal levels. In the Monte Largo area, however, the Tijeras fault zone does parallel subvertical Proterozoic foliations and on a larger scale, the fault crudely parallels both the strike of regional foliation and the southern margin of the Sandia pluton. The latter may suggest the pluton was preferentially derived from this block of crust and/or that magma may have ascended along deeper conduits and high-strain zones, in an ancestral Tijeras fault.

Similarly, other transfer zones of the rift seem to parallel Proterozoic high-strain zones. The Embudo transfer zone is generally related to the Pilar and related shear zones (Bauer and Helper, 1994); the Socorro transfer zone is related to the Morenci lineament (Chapin et al., 1978), which in turn may reflect the NE Proterozoic foliation (Mayo, 1958). Overall, we support the concept that NE-trending transfer zones may correspond to a fundamental NE-striking anisotropy of the crust that dates back to the time of Paleoproterozoic assembly of the lithosphere. However, we note that this probably represents more than simple mechanical reactivation of foliation planes.

At 1.44 Ga, the crust that now constitutes the Sandia Mountains was intruded by the Sandia Granite (Kirby et al., 1995). This pluton was emplaced synchronously with a NW-dipping extensional shear zone at its SE side (base). The pluton does not crop out SE of the Tijeras-Gutierrez fault system. It has a subhorizontal roof zone exposed near the Sandia ski area and in the Monte Largo Hills (Fergusen et al., 1996), it has a subvertical NW margin, and, based on the presence of Proterozoic rhyolite in the Montezuma uplift, apparently does not extend much NE of its present outcrop limits. Because of this spatial association, it is tempting to view the structural distinctiveness of the present Sandia Mountains block as related in some way (e.g., volumetric inheritance) to the Sandia Granite. Very similar1.4-Ga granites are exposed to the northwest in the Nacimiento uplift, beneath the Jemez caldera, and also in the Sangre de Cristo Mountains.

NE-striking thrust-sense shear zones in the Manzanita thrust belt to the south were reactivated at ca. 1.4 Ga (Brown et al., this volume), and penetrative contractional strain was important and widespread in northern New Mexico at this time (Williams et al., 1999). The Tijeras-Cañoncito fault zone strikes subparallel to the Vincent Moore shear zone, which is the frontal exposed thrust of the Manzanita thrust belt (Fig. 1). Because of the importance of both 1.65- and 1.4-Ga age deformations in producing the present Proterozoic fabric, foliation patterns and the NE grain in the basement should be considered as the composite effect of 1.65- and 1.4-Ga tectonism. Uncertainty exists as to which event provided the dominant control on local orientations (Thompson et al., 1996; Williams et al., 1999; Marcoline et al., 1999).

At 1.3–1.1 Ga, the region underwent Grenville tectonism as arc terranes collided with North America in the Texas area (Mosher, 1998). At about the same time, the continent was extended at high angle to a collisional front and intruded by mafic magmas along the mid-continent rift and central basin platform (Adams and Miller, 1995). Rocks of 1.3–1.1 Ga are absent in the Sandia area, but, diabase intrusive rocks of probable 1.1-Ga age crop out in the Sacramento Mountains (Pray, 1961) and appear to be related to a Proterozoic failed rift zone based on a major magnetic high (SE region of Fig. 2, Plate T; Broadhead, 1997). By analogy to other regions in the Southwest (Karlstrom and Humphreys, 1998; Timmons et al. in review), we speculate that this episode may have resulted in NW-striking extensional structures and NE-striking contractional structures.

In support of this idea, at least some of the NW structures shown in Figure 2 (and Plate T) are pre-Pennsylvanian. For example, a zone that extends through the southern Nacimiento and Sandia mountains was intruded by Late Precambrian–Cambrian alkalic dikes (Loring and Armstrong, 1980; McLemore et al., this volume); other NW zones form margins of Pennsylvanian basins and hence were likely reactivated intracratonic structures (Grant and Foster, 1989); NW-trending faults are truncated locally at the Pennsylvanian unconformity (La Cueva structure of Kelley and Northrop, 1975); and NW-trending lineaments form deep-seated features defined by ore deposit trends and geophysical gradients (Fig. 2; Plate U). In the Apache and Unkar Groups of Arizona and the Death Valley region of California, late Proterozoic sedimentary rocks of 1.2–1.1 Ga are interpreted to be syntectonic with respect to this deformation. Scattered outcrops of similar-age sedimentary rocks are preserved in the Sacramento Mountains area (Pray, 1961) and Franklin Mountians, and these suggest the presence of regional, fault-bounded basins. A pervasive NW trend, which corresponds to some of the lineaments in Figure 2 (Plate T), is also evident on gravity maps of the Albuquerque basin (Plate A).

At 800 Ma, E–W extension on N–S faults took place in the Grand Canyon region; this extension may also have influenced the development of the N–S Rocky Mountain trend (Timmons et al., in review). No rocks of this age are present in the southern Rocky Mountains. However, $^{40}Ar/^{39}Ar$ dating of K-feldspars suggests that presently-exposed Precambrian rocks were still deep and that a regional reheating and/or unroofing event took place at this time. Harrison and Burke (1989) reported K-feldspar $^{40}Ar/^{39}Ar$ results from the Fenton Hill drill core from the Valles Caldera. Despite the fact that the samples span a depth profile of ~1.8 km, all initial ages in the K-feldspar age spectra are ~850 Ma. This result is consistent with either a reheating event, which partially reset the K-feldspars, or a cooling event related to rapid denudation at ca. 850 Ma. These authors also reported a single K-feldspar argon age spectrum from the Sandia Granite, having a segment

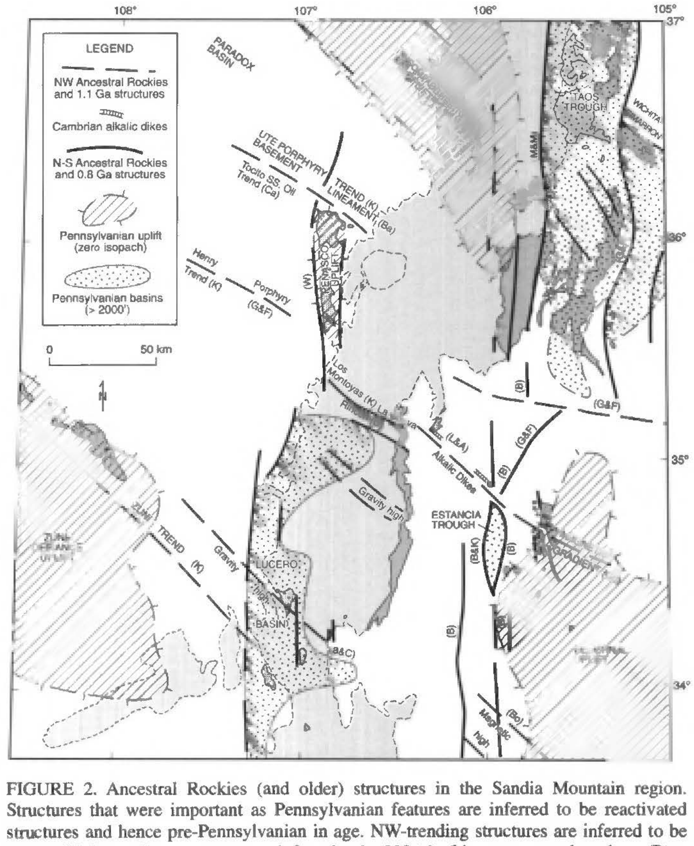

FIGURE 2. Ancestral Rockies (and older) structures in the Sandia Mountain region. Structures that were important as Pennsylvanian features are inferred to be reactivated structures and hence pre-Pennsylvanian in age. NW-trending structures are inferred to be 1.1 Ga. N–S-trending structures are inferred to be 800 Ma. Lineaments are based on: (B) = Broadhead (1997); (B&C) = Beck and Chapin (1994); (B&K) = Barrow and Keller (1994); (Ba) = Baars, 1982; (Bo) = Bowsher (1994), (C) = Connell et al. (in preparation), (Ca) = Cather (in press), (Co) = Cordell (1984); (G&F) = Grant and Foster (1989); (K) = Kelley (1955); (L&A) = Loring and Armstrong (1980); (M&M) = Miller et al. (1963); (S) = Soegaard (1990); (W) = Woodward (1996).

that is ~800 Ma followed by an age gradient where the ages rise to ~1050 Ma. Heizler and Ralser (1994) and Heizler (1998) have further interpreted the Sandia data and suggest that the recorded age gradient is related to argon loss associated with an 800–850 Ma reheating event. Elsewhere in the region, K-feldspar argon data argue for relatively rapid cooling between ca. 800 to 850 Ma. For instance, a sample from the Santa Fe Range has an age spectrum which is nearly flat at 800 Ma and is clearly indicative of rapid cooling at this time. Also, results from the Wet Mountains, Colorado, are similar to those of central and northern New Mexico and show accelerated cooling during this time period (Heizler, 1998). It is difficult to extrapolate the thermochronologic signature to the geological evolution, but it is possible that widespread cooling and/or reheating at ca. 800 Ma reflect regional hydrothermal and extensional activity related to the incipient breakup of Rodinia. Ongoing $^{40}Ar/^{39}Ar$ thermochronologic studies of K-feldspars from Paleo- and Mesoproterozoic terranes may hold the key to understanding the geologic history for a time period for which little rock record is preserved.

ANCESTRAL ROCKIES TECTONISM

The oldest post-Precambrian deformation to affect the Sandia Mountains region was the ancestral Rocky Mountain event. In Mississippian through Early Permian time, the Sandia region received sediment from the adjacent N- or NW-trending Pedernal uplift (Fig. 2, Plate T). Preserved sediment thicknesses are highly variable, and there is evidence for nearby deep fault-bounded basins indicating that N–S and NW structures were perhaps already in existence and helped control ancestral Rockies uplifts. For example, deep Pennsylvanian troughs (Taos, Estancia, Lucero; Fig. 2) were important late Paleozoic depocenters that were bounded principally by N–S high-angle faults, similar to Laramide structures (Soegaard, 1990). A precursor to the Sierra Nacimiento (Peñasco uplift) seems to have been a N–S trending uplift (Woodward, 1996) and was perhaps the northern part of a N–S high in the Albuquerque basin (Kelley, 1955; Baars, 1982). The Zuni-Defiance uplift was a broad NW-trending high, as was the Uncompahgre uplift. Models differ on the kinematics of this deformation—sinistral shear due to Ouachita collision to the SE (Kluth and Coney,1981; Budnick, 1986) versus far field compression from the SW (Ye et al. 1996), but all workers agree that deformation was driven by far field stresses and involved reactivation of older structures.

Several faults of possible Pennsylvanian age have been identified in the Sandia Mountains: NW-striking faults across which thickness of Mississippian and Pennsylvanian strata change (Ferguson et al., 1996), highly silicified NW-striking structures in the Sandia Crest Quadrangle (Read et al., 1995), and the pre-Sandia Formation La Cueva fault and related structures in the Sandia Granite on the western face of the Sandia Mountains (Kelley and Northrop, 1975; Fig. 2, Plate T). Also, NW-trending basin structures like the Los Moyas fault (Kelley and Northrop, 1975) and NW-trending gravity highs in the Albuquerque basin (Grauch et al. this volume) may have ancestral Rockies (and ultimately Grenville) ancestry. North- and NW-striking faults of late Paleozoic age have also been described in the Joyita Hills (mostly normal; Beck and Chapin, 1994) and Sacramento Mountains (Pray, 1961). Clearly, by the Pennsylvanian, there is evidence for a mosaic of NE, NW, and N–S structures and a fault-segmented crust.

LARAMIDE OROGENY

Our view of the Late Cretaceous–early Tertiary (Laramide) orogeny is that NE subhorizontal contraction was imposed on a strongly segmented crust, with resulting heterogeneity of deformation. Regional Laramide (80–40 Ma) structures in northern and central New Mexico have recently been summarized by Cather (in press) and Woodward et al. (this volume). It seems clear that the Sandia block was within the Laramide Southern Rocky Mountains that extended from Wyoming to New Mexico. But judging from the throw on frontal faults, range-front relief in Rocky Mountain uplifts may have decreased sharply from the Sangre de Cristo Mountains south to the Sandia-Manzano (Montosa) uplift. The average regional contraction direction was NE, although it probably varied systematically through time (Chapin and Cather, 1981; Erslev, 1998). Many faults had significant dextral strike-slip components (Cather, in press). This transpressional deformation records an unresolved combination of partitioned oblique slip on pre-existing structures (this paper) and development of neoformed structures of diverse orientation within rotating or changing stress fields (Erslev, 1998). From many lines of evidence we infer that the basic right-stepping configuration of the Rio Grande rift mimics a Laramide right-stepping oblique-slip deformation system.

Laramide structures in the Sandia-Manzano Mountains have been recognized for many years (e.g., Kelley and Northrop, 1975). The best-accepted structure is the Montosa fault zone of the Manzano Mountains, a Laramide reverse fault and associated monocline, also with documented right-lateral strike slip of unknown magnitude (Hayden, 1991). We consider the Montosa structure to be analogous to frontal faults of the Sangre de Cristo Mountains. The Montosa fault curves to the west of the Manzano Mountains along a zone of NW-trending gravity highs and disappears beneath Tertiary sediments (Fig. 3). However, subsidiary contractional faults also continue north on the eastern side of the range and connect with the Tijeras-Cañoncito fault system (Fig. 3, Plate U; Ferguson et al. 1996).

The Tijeras-Cañoncito fault system has long been thought to have Laramide movement (Abbott et al., 1995), but senses and timing of displacements have been debated. This fault system exhibits both contractional and extensional deformation. Shortening structures (folds and overturned beds) are best developed in the southwestern part of the system, where reverse dip separation is about 1000–1200 m (Ferguson et al., 1996). Normal faulting seems to predominate to the NE of the Monte Largo Precambrian horst (Stearns, 1953). The apparent kinematic diversity is probably best reconciled by strike slip during the Laramide along this fault system. Significant dextral slip is suggested by right stepping of the major shortening structures from the Montosa fault to the Sangre de Cristo Mountains, as well as by kinematic data (Abbott and Goodwin, 1995).

Although the locus of Laramide contraction may have stepped NE to the Sangre de Cristo Range along the Tijeras-Cañoncito system, a series

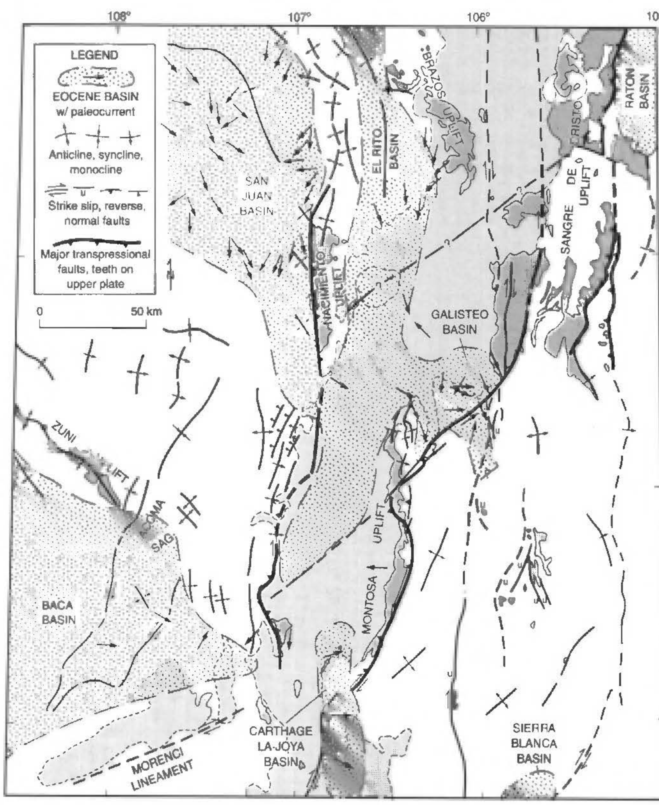

FIGURE 3. Laramide basins, faults, and folds of northern and central New Mexico; adapted from Cather, in press.

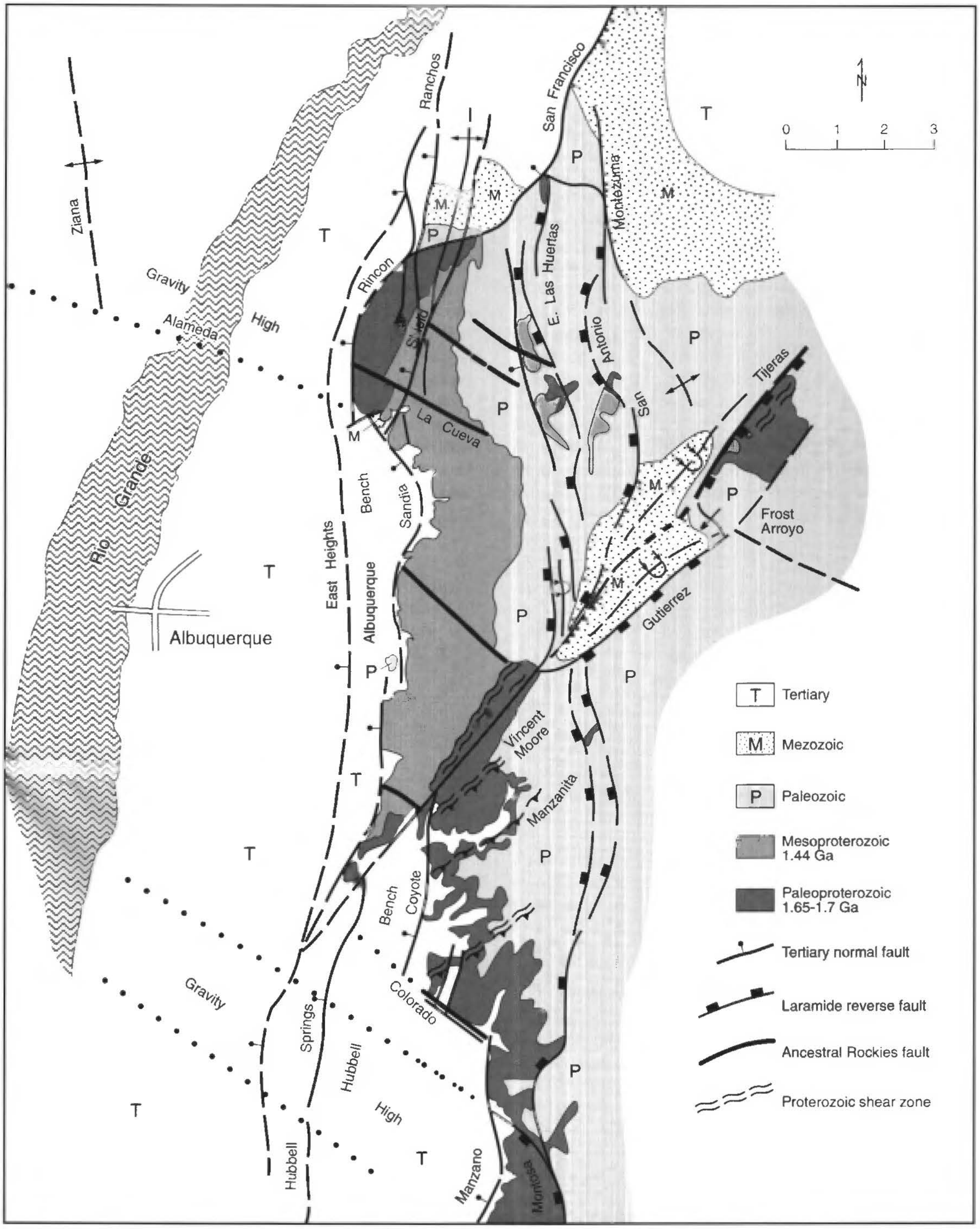

FIGURE 4. Geology of the Sandia Mountains region, showing the positions of Laramide features; adapted from Kelley and Northrop (1977), Ferguson et al. (1996), Karlstrom et al. (1995), Connell et al. (1995), and Read et al. (1995).

of contractional faults and overturned folds continue north of the Tijeras fault and mark a continuation of the Montosa trend along the eastern side of the Sandia Mountains. These include the Cañoncito-Flat Iron faults, San Antonio fault system, the East Las Huertas fault, and the Montezuma structure (Fig. 4, Plate V; Kelley and Northrop, 1977; Connell et al., 1995; Ferguson et al., 1996). Reverse dip separation on individual faults was generally less than about 100 m, although many of these faults were reactivated with normal slip in the Miocene, so it is not possible to determine magnitude of Laramide reverse separation.

Based on the nature of these structures, we hypothesize that the Laramide-age Sandia uplift was a part of an east-verging asymmetrical anticline/monocline that extended from Placitas to the Los Pinos Mountains. In this view, Laramide structure was analogous (as mirror image) to the west-facing Nacimiento Mountains in several respects. First, the main "Front Range" fault is expressed (in both) as oppositely verging reverse faults and associated monoclines. Second, both are broad doubly-plunging anticlinoria with complex segmentation due to transfer zones. Finally, both were covered by thick Mesozoic sedimentary sequences and did not shed Precambrian detritus into adjacent Laramide basins. The rising Nacimiento uplift influenced regional sediment dispersal patterns (Smith, 1988; Cather, 1992), and Laramide apatite fission-track (AFT) cooling dates are preserved in the

Nacimiento Mountains such that the timing of denudation coincides well with the development of an angular unconformity at the base of the Eocene San Jose Formation (Baltz, 1967; Pazzaglia and Kelley, 1998).

The sedimentary evidence for a Sandia Laramide uplift is less clear than for the Nacimientos. Provenance and paleocurrent data however, do not rule out modest Laramide uplift in the Sandia area, if such uplift produced low topography or perhaps only intrabasinal thinning within the Galisteo basin. Paleocurrents in the Galisteo basin to the east of the Sandias are southeast-directed (Fig. 3, Plate U) and do not show evidence for proximal sources. This is similar to the Nacimientos, which apparently shed little coarse-grained detritus into the adjacent syntectonic San Juan Basin (Smith, 1988). Thus we envision both areas as anticlines that were still covered with Paleozoic and Mesozoic rocks (including Cretaceous shales) and hence resembled the monoclinal uplifts of the Colorado Plateau perhaps more than the basement-cored Colorado front ranges. Sedimentary evidence for multiple source areas, variable paleocurrents, unroofing sequences, and an angular unconformity due to southeast-tilting of the Galisteo basin (Gorman and Ingersoll, 1979; Lucas et al., 1995) are all compatible with a Laramide ancestry for the Sandia uplift. Although not proposed by Abbott et al. (1995), the complex but locally E- and NE-directed paleocurrents in the Hagan basin trend away from the Sandia Mountains and are also compatible with this interpretation.

TECTONIC EVOLUTION OF THE PLACITAS AREA

The north-dipping ramp at the northern end of the Sandia block near Placitas is a key region to evaluate the relative importance of Laramide versus Miocene tectonism in producing the present geometry of the Sandia Mountains. Paleozoic and Mesozoic strata dip about 30–60° north and define a fault-related north-dipping homocline or part of a faulted north-plunging anticline. In simplest terms, faults can be divided into two principal sets (Fig. 5): (1) north-striking faults with mostly west-down stratigraphic separation, and (2) east or east-northeast striking faults with mostly north-down separation. Both sets have normal separation, but at least two of the north-striking faults (East Las Huertas and Agua Sarca faults; Fig. 5) show evidence of having been inverted from Laramide reverse faults (Connell et al., 1995). Both east- and north-striking sets of faults are steep at the surface (>70°) and are best-developed in pre-Neogene rocks; a few faults of both sets also cut or bound the Santa Fe Group. Faults of the Placitas area have been described by Menne (1989) and Woodward and Menne (1995). Here we focus on faults which show the greatest stratigraphic separation or those for which kinematics have been determined.

Several models for the structural development of the Placitas area have been proposed. Kelley (1982) inferred that sinistral components of extension in the rift produced several "relay ramps" along the margin of the rift, one of which is the north-dipping homocline in the Placitas area. It is difficult to evaluate Kelley's model because the relative importance of E–W extension versus sinistral strike-slip was not explicitly stated. If Kelley (1982) intended the sinistral component to be dominant (e.g., his fig. 2c.) then his "relay ramps" would represent (using current terminology) restraining bends between right-stepping sinistral faults. We feel that this interpretation is implausible because of the lack of shortening structures (folds, thrusts) along the Placitas fault zone that would be predicted for such a restraining bend. Kelley (1982) may have envisioned subequal extension and sinistral strike-slip or a dominance of extension (e.g. SW–NE extension) along the rift. This scenario is plausible to explain the ramp structure (see below), although incapable of explaining all the geologic features present near Placitas.

Russell and Snelson (1994) and Woodward and Menne (1995) interpreted the Placitas fault system to be the low-angle listric root of the San Francisco fault that was tilted northward and exposed by Neogene uplift of the Sandia block to the south. To support their interpretations, these workers utilize a "down-structure" perspective and view the map parallel to the dip direction of beds in the northern homoclinal termination of the Sandia uplift. However, Mackin's (1950) down-structure method, which is designed for cylindrical fold systems, is inappropriate for interpreting faults of the Placitas region. It gives a false impression of the dip of the Placitas fault system because the E–W strike of faults is normal to the homocline dip direction, thus yielding an apparent subhorizontal dip. This violates field observations of linear traces of faults across the rugged topography of the northern Sandia foothills and measured steep to subvertical dips (Figs. 5, 6; Menne, 1989; Connell et al., 1995). To restore the Placitas fault system to original subhorizontality as envisioned by Russell and Snelson (1995) and Woodward and Menne (1995) would require much more than simply removing the northward homoclinal dip near Placitas, which would leave the Placitas fault system with dips of 50–60° to the north (Fig. 6).

Interpretations of seismic data west of the Placitas region (line 50 of Russell and Snelson, 1994) suggest that the San Francisco-Placitas fault may flatten to low dips at depths of about 3 km, then merge with (or be cut by) a major detachment (their Rio Grande fault) at depths of about 6 km. However, their cross section is difficult to reconcile with the steep westward dips (67–78°) on the San Francisco fault in outcrop and the absence of east-tilted strata that would be predicted from listric faulting. Instead of a detachment with thin basement slivers above it, the observed semi-continuous west-dipping reflection from 2.4–3.6 seconds in line 50 seems more likely to be the great unconformity. Given the lack of borehole or seismic control between the trace of the San Francisco fault and seismic line 50 to the west, we remain uncon-

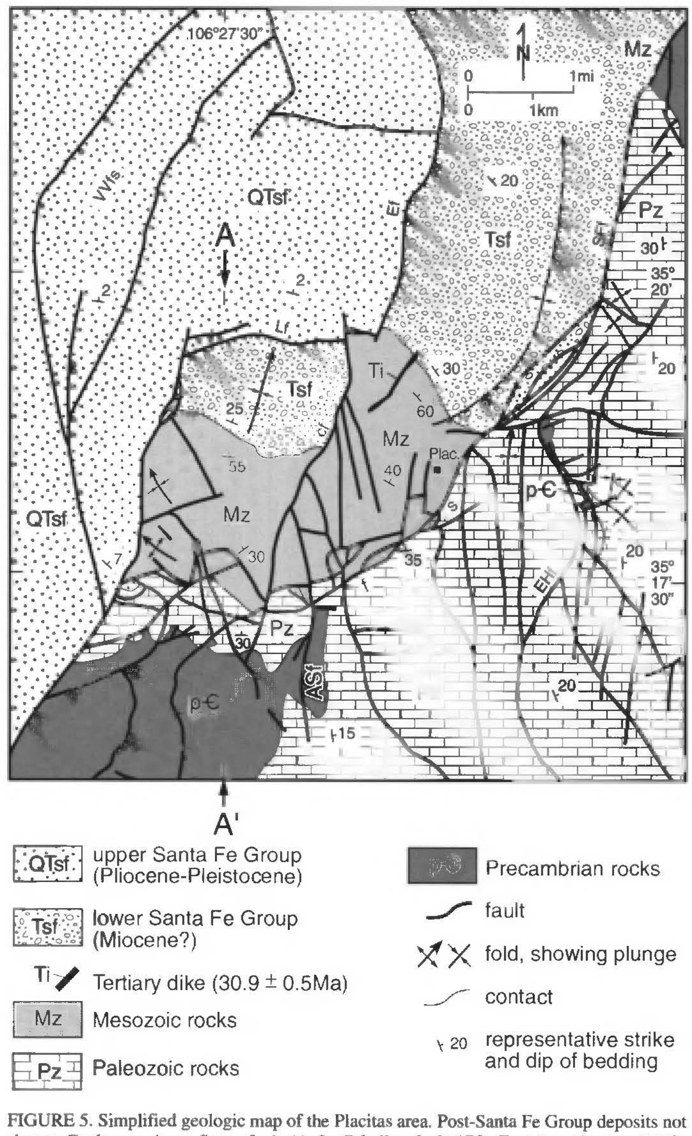

FIGURE 5. Simplified geologic map of the Placitas area. Post-Santa Fe Group deposits not shown. Faults are Aqua Sarca fault (Asf), Caballos fault (Cf), East Las Huertas (EHf), Escala fault (Ef), Lomos Fault (Lf), Placitas fault zone (Pfz), Rincon fault (Rf), San Francisco fault (SFf), Valley View fault system (VVfs). Mu = Montezuma uplift, Plac. = Placitas. A–A' is line of section for Figure 6. Modified from Connell et al. (1995).

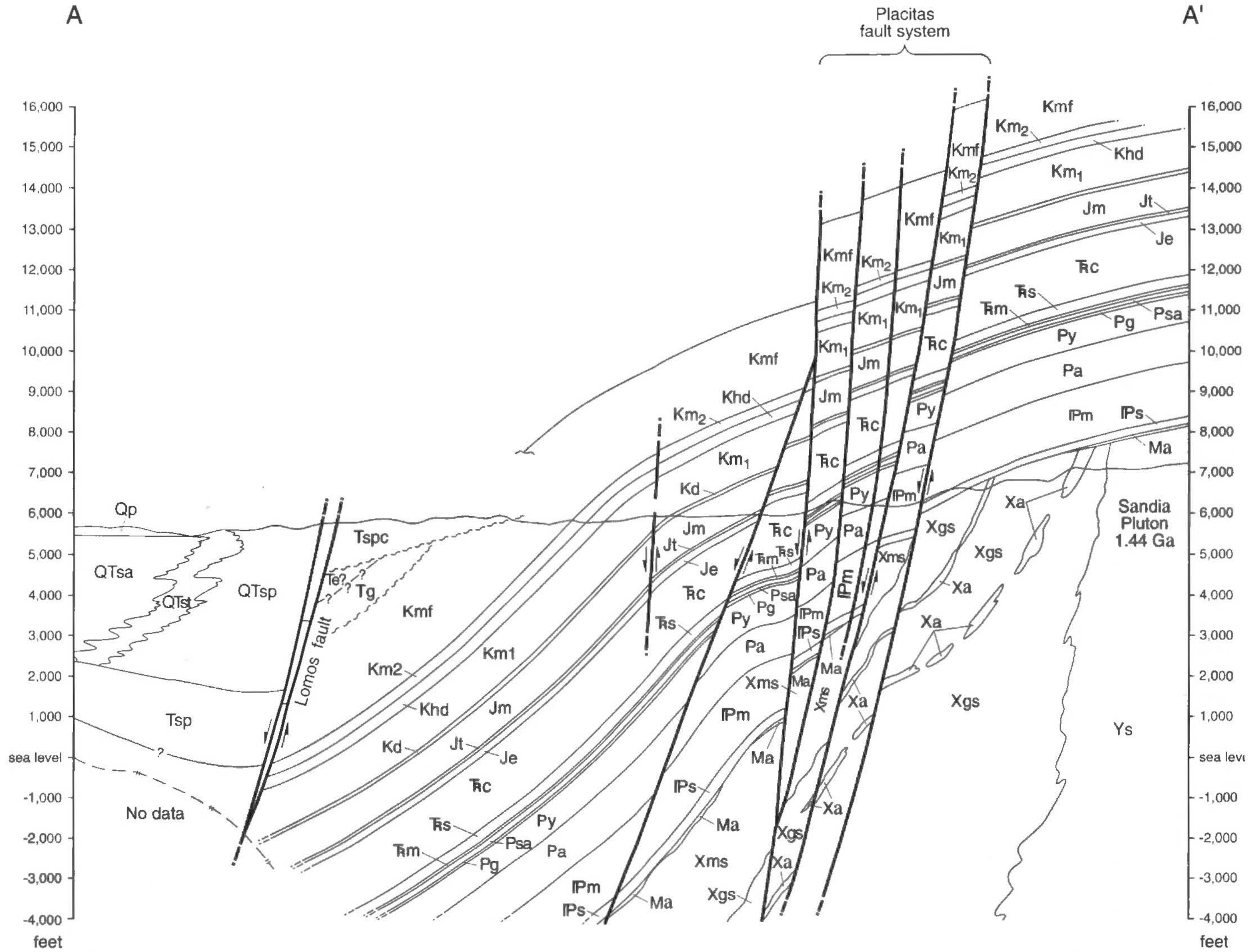

FIGURE 6. North–south cross section through Placitas fault system and homocline at northern end of Sandia block (Connell et al., 1995); line of section is 106°27'30 (no vertical exaggeration). Note steep dips of normal faults, and that restoration of beds to horizontal produces fault dips more typical of normal faults (50–60°).

vinced by the seismic interpretation of Russell and Snelson (1994).

Any plausible tectonic model for the Placitas area must account for several observations: (1) faults have steep dips (>70°) and there is lateral linkage between the principal faults in the area (Rincon, Placitas, East Las Huertas, and San Francisco faults). (2) the 30–60° northward-dipping homocline in Mesozoic and Paleozoic rocks is present on both sides of the Placitas fault system, with near continuity of the Madera Formation outcrops from Sandia crest to the ramp; (3) some faults (Agua Sarca, East Las Huertas, Montezuma) are related to monoclinal bends, are demonstrably contractional, and hence are likely to be of Laramide age; (4) there is a ~30° angular unconformity (Fig. 5) between basal Santa Fe beds and underlying Mesozoic strata; and (5) there are two distinct sets of folds: an older set of dominantly NW-trending folds developed in the Mesozoic and Paleozoic strata, and a younger set of NNE-trending synclines in the Santa Fe group.

We propose a two-stage tectonic model for the Placitas area that includes elements of both Laramide and Rio Grande rift deformation (Fig. 7). Several structures are interpreted to have resulted from NE Laramide shortening. There are broad NW-trending folds oblique to the strike of the Rincon, San Francisco, and East Las Huertas faults; these suggest right lateral components of slip along these faults. Kinematic indicators along the Agua Sarca fault are also indicative of dextral components of slip (Connell et al., 1995). North-trending, east-verging monoclinal structures of the Agua Sarca, East Las Huertas, and Montezuma structures (Fig. 7) record basement-cored, tight monoclines, locally with overturned bedding (East Las Huertas) that mimics the steep west-dip of these faults. The NW-trending Montezuma block (Kelley and Northrop, 1977; Connell et al., 1995) is a contractional structure. NW-striking segments of the East Las Huertas fault show evidence of contraction, suggesting development of a restraining bend due to a dextral strike-slip component. We speculate that the Rincon and San Francisco faults, which are both subparallel to the East Las Huertas fault, also may have been active as reverse faults in the Laramide. These faults are presently west-down normal faults, but may have been inverted from monoclines that formed over transpressive faults.

The Placitas fault system acted as a relay between the Rincon and San Francisco faults. We interpret dextral components of slip on these latter two faults (as shown by oblique folds) to have caused transtensional deformation across the Placitas fault system, resulting in the initial development of the north-dipping normal faults of this system (Fig. 7a). Our interpretation of a Laramide inception for the ENE-striking normal faults of the Placitas fault system is compatible with previous interpretations of NE-striking Laramide normal faults in adjacent areas (Rio Puerco fault system: Slack and Campbell, 1976; northeastern part of the Tijeras-Cañoncito fault system: Stearns, 1953; Cather, 1992). Presently about 1300 m of north-down stratigraphic separation of Mesozoic strata exists across the Placitas fault zone (Fig. 6). An unknown part (perhaps all) of this displacement may be Laramide. However, the Lomos fault (Fig. 5), which parallels the Placitas fault system about 3.5 km to the north, cuts the Santa Fe Group and thus was active during the

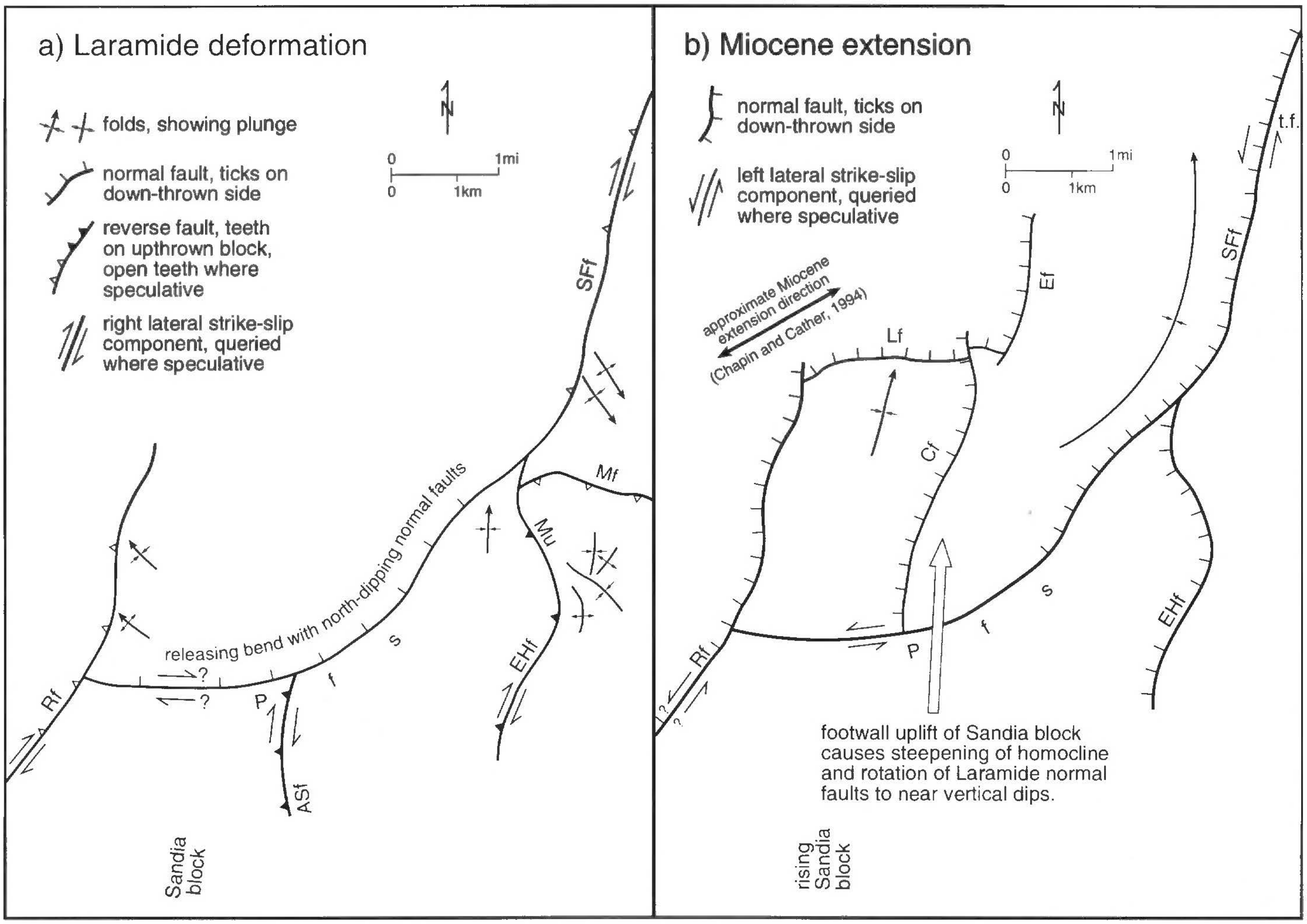

FIGURE 7. Two-stage model for structural development of Placitas area, highly simplified to show principal faults and fault systems. Folds are divided into younger and older sets on the basis of orientation and age of host rocks. **a**, Laramide kinematic model: Agua Sarca fault (ASf), East Las Huertas fault (EHf), Montezuma fault (Mf), Rincon fault (Rf), and San Francisco fault (SFf) are interpreted to represent Laramide dextral oblique reverse faults. Folds in Paleozoic and Mesozoic rocks (most trend NW) are oblique to the strike of adjacent faults and thus suggest dextral slip. The Placitas fault system was active as down-to-the-north normal faults (also possibly dextral) that developed as a right-stepping releasing bend between the Rincon and San Francisco – East Las Huertas systems. Mu = Montezuma uplift. **b**, Miocene kinematic model: NE–SW extension causes left-oblique normal slip on north-northeast striking Rincon and San Francisco faults and inversion of Laramide reverse displacement on these faults and the East Las Huertas fault. Placitas fault zone experienced mostly sinistral strike slip, although significant down-to-north normal components of slip may also have occurred early in Miocene deformation. Footwall uplift of Sandia block by tectonic denudation along Rincon and Sandia faults caused steepening of homocline at north end of block and rotation of Laramide normal faults of Placitas fault zone to subvertical dips. Other important normal faults are Caballo fault (Cf), Lomas fault (Lf), and Escala fault (Ef).

Neogene. Thus, the Placitas fault system may have been reactivated during the Neogene.

North and west of the town of Placitas, lower Santa Fe Group rocks unconformably overlie Mesozoic rocks with ~30° angularity (Fig. 5). The Santa Fe Group above this unconformity is younger than the 30.9 Ma dike that it buries near Placitas and older than the 1.6 Ma Bandelier ash beds present high in the section ~12 km to the north on San Felipe Pueblo lands. We suspect on the basis of moderate induration and moderate (20–30°) NE dip that the basal Santa Fe in this area is Miocene. Restoration of basal Santa Fe Group beds to horizontal leaves ~30° northeast tilt on underlying beds. Paleomagnetic data for the 30.9 Ma dike near Placitas suggest that most or all of the stratal rotation in this area occurred subsequent to dike intrusion (Anders and Geissman, this volume). Thus, the angular unconformity near Placitas appears to have formed after 30.9 Ma, the result of tilting and erosion of the Sandia block prior to the onlap of basal Santa Fe beds (Miocene?) in this area.

Miocene extension in the rift was NE–SW-directed (Chapin and Cather, 1994), an orientation that favors left-oblique normal slip on north-trending faults (Fig. 7b). En echelon arrays of calcite-filled extension fractures in limestone of the Madera Formation near Stop 3 (First-day Road Log, this volume), are suggestive of left slip on the San Francisco fault (we speculate that these fractures are rift-related). Left-slip may have also accompanied normal faulting on the Rincon fault, but this cannot be proven or disproven with available data. NNE-trending synclines in the Santa Fe Group may be growth synclines related to west-down faulting on the San Francisco and Caballo structures (Fig. 7b).

During the Miocene the strike of the Placitas fault system was subparallel to the regional extension direction, and the fault system may have acted as a left-lateral relay between the San Francisco and Rincon structures. This hypothesis is supported by the presence of subhorizontal left-lateral slickenlines recently found on a minor fault within the Placitas fault system (S. Minor, 1999, oral commun.). North-down normal faulting may have continued during the early part of rifting, and normal faults may have tilted to progressively steeper dips due to the Miocene footwall uplift of the Sandia block. The notably non-Andersonian steep dips of the normal faults of the Placitas system (Fig. 6) thus may be the result of subsequent homoclinal rotation of about 30°, enough to tilt the Santa Fe Group and its basal unconformity.

The San Francisco and Placitas fault systems appear to be no longer active. Both structures are locally buried by post-Santa Fe deposits of late Pliocene–early Pleistocene age (Connell and Wells, this volume). Recent faulting appears to have stepped basinward to the Rincon and

Valley View as well as faults farther west (Russell and Snelson, 1994; Connell and Wells, this volume). Southwest-directed extension, which characterized deformation during the volumetrically dominant middle to late Miocene phase of Santa Fe Group sedimentation, may have given way to west-northwest extension in latest Miocene time. Rakes of slickenlines on N-striking normal faults that cut Plio-Pleistocene rocks in the northern Albuquerque basin are indicative of dextral oblique extension across the rift (R. M. Chamberlin, 1998, oral commun.; G. A. Smith oral commun., 1998; S. Minor, 1999, oral commun.). These observations are compatible with the cessation of sedimentation in E–W trending extensional basins (Browns Park, Split Rock, and Circle Bar basins) north of the Colorado Plateau in the late Miocene (Chapin and Cather, 1994), as would be predicted by renewed north-directed motion of the Colorado Plateau relative to the craton. Thus, with the exception of sinistral displacements during Miocene SW extension, dextral components of slip seem to have characterized deformation along northerly striking faults in the Rio Grande rift-Southern Rocky Mountains area throughout the Tertiary and Quaternary.

APATITE FISSION-TRACK DATA

Present differences in elevation and tilt of rift flanks in the Sandias, Manzanitas, Manzano and Los Pinos uplifts may be in part of Laramide origin (Kelley and Northrop, 1975), but where accentuated by Tertiary block segmentation, differential tilting, and rift-flank uplift (Roy et al. this volume). Kelley and Duncan (1986) and Kelley et al. (1992) conducted a regional AFT thermochronology study to examine the relative cooling histories of these blocks along the eastern margin of the Rio Grande rift. The AFT dates increase toward the south, indicating larger amounts of Laramide denudation in the Los Pinos Mountains relative to the Sandia and Manzano mountains and greater post-Laramide denudation of the Sandia Mountains compared to ranges to the south. AFT dates along age-elevation traverses in the Sandia Mountains are 14.2 ± 1.9 (1 standard error) Ma at low elevation to 30.4 ± 2.5 Ma at high elevation, 20.1 ± 4.8 to 47.7 ± 5.5 Ma in the Manzano Mountains, and 44.1 ± 6.5 to 65.4 ± 20 Ma in the Los Pinos Mountains. Abbott (1995) found no difference in the AFT ages of bedrock units on either side of the Tijeras fault zone in the vicinity of the Monte Largo horst (21.4 ± 3.3 to 25.9 ± 2.6 Ma) or in Tijeras Canyon (23 ± 3.1 Ma and 20.1 ± 5.0 Ma), suggesting that this structure had little appreciable dip slip after 20 Ma.

AFT dates and track-length data from high-elevation samples suggest that the Manzano Mountains began cooling before the Sandia Mountains and that the rate of cooling was slower (3–4°C/m.y in the Manzano Mountains compared to 7–12°C/m.y. in the Sandia Mountains: Kelley: et al., 1992). This is compatible with a higher relief part of the Montosa uplift being erosionally denuded (and cooled through the 60–120°C temperature range) before the Sandia block. K-feldspar $^{40}Ar/^{39}Ar$ results from the Manzano Mountains indicate that rocks cooled through ~200°C at 60 Ma and, considering the AFT results, suggest that uplift began in the Laramide at about this time and continued through the fission-track temperature window at about 40 Ma.

The apatite fission-track dates from below the crest of the Sandia Mountains unambiguously indicate that the granites near the great unconformity cooled relatively quickly through 60–120°C at about 30 Ma. The sample traverse is distant from localized thermal effects of the Ortiz-Cerrillos volcanic field, and we interpret the AFT date to reflect the time of stripping of overburden and resulting cooling below about 120°C. Assuming normal geothermal gradients, the rocks would have been at depths of at least 3 km before 30 Ma. K-feldspar $^{40}Ar/^{39}Ar$ from the Sandia Granite also suggests temperatures of at least 150°C during maximum burial. Thus the entire Paleozoic and Mesozoic section (about 3 km) was still present, and the Sandia granitic basement had not been significantly denuded before 30 Ma. Exhumation then took place between 30 and 14 Ma. This is compatible with minor erosional unroofing of a small-scale Laramide structure in the northern Sandia Mountains, but is not necessarily the time of a discrete episode of extensional tectonism.

Regionally, there is increasing evidence that AFT data can be interpreted in terms of a multistage denudation of the Rocky Mountain region (Pazzaglia and Kelley, 1998). Both geologic and AFT data from the Southern Rocky Mountain/High Plains boundary in Colorado and New Mexico suggest Late Cretaceous–late Eocene denudation associated with Laramide contraction. Renewed regional denudation occurred between 30 and 15 Ma, possibly due to: (1) continued deformation (contraction or strike slip: Erslev, 1998); (2) climate change and exhumation of older structural uplifts; and/or (3) epeirogenic uplift due to buoyant mantle upwelling and associated regional volcanism (Roy et al., this volume). The AFT data from the Sandia and Manzano Mountains are similar to AFT results from the High Plains and eastern Sangre de Cristo Mountains, and may record a regional late Oligocene to early Miocene denudation (Kelley and Chapin, 1995). Very young fission-track dates of <10–15 Ma (e.g., Ladron Mountains: Kelley et al., 1992) are likely related to rift-flank uplift during extension, as discussed by Roy et al. (this volume).

CONCLUSIONS

The crust of the Sandia-Manzano uplift is pervasively segmented by faults that record about 1.7 billion years of middle and upper crustal deformation. NE-trending structures originated in the Paleoproterozoic (1.65 Ga), were accentuated in the Mesoproterozoic (1.4 Ga), contributed to the shape of Laramide right-stepping oblique-slip faults, and were important as transfer systems in Miocene extension that formed the Rio Grande rift.

NW-trending structures probably originated during the time of the Grenville orogeny as the continent was compressed from the SE and extended NE–SW. Major lineament systems (Texas, Zuni, Uncompahgre) may be related to extensional systems of this age as suggested, especially in Arizona and southern New Mexico, by Mesoproterozoic sedimentary rocks. These NW-trending structures were reactivated in ancestral Rocky Mountains deformation, formed important contractional structures of the Laramide orogeny, and are expressed as minor transfer zones and lineaments in the Rio Grande rift.

The N–S trend of the Rocky Mountains and Rio Grande rift may have initiated at about 0.8 Ga, during E–W extension associated with breakup of the Rodinia supercontinent. Evidence includes synextensional sediments in the Grand Canyon region and a major 800–Ma thermal event seen in $^{40}Ar/^{39}Ar$ thermochronologic data in the southern Rocky Mountains. We speculate that the area of the Rio Grande rift was a major N–S graben system at this time.

Laramide contraction utilized many older structural features of diverse trend, giving rise to heterogeneous block uplifts. Although some structures in the Rio Grande rift area of New Mexico (Sandias and Nacimientos) did not expose Precambrian rocks at this time, others did (Brazos, Pajarito, and Sierra uplifts). The region may have consisted of a segmented transpressive flower structure (Cather, 1992). The importance of Laramide contractional and transpressional structures in controlling the basic geometry of the rift and rift flanks has been underestimated.

The Rio Grande rift records extension and collapse of a Laramide highland due to a combination of gravity forces and possibly mantle upwelling. Tertiary extension inverted some Laramide structures and inherited much Laramide heterogeneity. The discrete nature of the Rio Grande rift in northern New Mexico reflects some unresolved combination of the preexisting geometry of faults, high elevations in this region, and the probability of major mantle upwelling along the intersecting Jemez and Rocky Mountain lineaments.

Fission-track dates span much of the Laramide and Tertiary and seem to record progressive and segmented exhumation during several events. AFT data from the Los Pinos, Nacimiento, and Santa Fe Range record cooling associated with Laramide deformation from 70 to 50 Ma. The AFT data from the Sandia-Manzano-Los Pinos Mountain chain indicate that denudation associated with Laramide deformation was greater toward the south. However, during late Eocene–early Miocene time, the denudation trend reversed, so that denudation was greater towards the north. The AFT data from the Sandia and Manzano mountains appear to record middle Cenozoic (30–20 Ma) denudation that is also observed in the eastern Sangre de Cristo Mountains and on the High Plains (Kelley and Chapin, 1995). Uplift and erosion associated with middle to late Miocene rifting are not recorded by AFT data from surface rocks in this area, but may be preserved in the subsurface.

Regional uplift models to explain the combined geologic and AFT data seem to require a multistage denudation history. Laramide contraction likely resulted in surface uplift of Cretaceous marine rocks accompanied and followed by fluvial erosion of Laramide highlands. We envision a segmented Laramide upland in the Rio Grande rift area by the late Eocene, with synorogenic basins and southeast flowing rivers. Epeirogenic uplift and formation of "Alvarado" ridge (Roy et al., this volume) is interpreted to have resulted from asthenospheric mantle upwelling and regional doming due to buoyancy introduced by hot upwelling mantle. We interpret the 30–20-Ma AFT dates to record cooling due to denudation by fluvial erosion of the uplifted region. This upwelling and upwarping may have overlapped volcanic flare-up in the Mogollon-Datil, Cerillos-Ortiz, Latir, and San Juan volcanic fields and early extension in the rift. Formation of the Rio Grande rift may reflect extensional collapse of overthickened and thermally weakened crust of the elevated region. Isostatic rift flank uplift due to Miocene extension may have accentuated an already heterogeneously segmented rift flank.

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Photo op during the usual morning wait for the cavavan to assemble finds Frank Schrempfl, ex-Chicago taxi driver and UNM student, with his professors Paul Fitzsimmons, Stu Northrop, and Sherm Wengerd, wondering why it takes so long to get on the road. Photograph taken on the third day of the 3rd field conference (October 5, 1952) with "M" Mountain rising above Socorro in the background (photograph courtesy of Florence Wengerd).