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PHANEROZOIC GEOLOGIC EVOLUTION OF THE ALBUQUERQUE AREA

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Abstract—Global changes at geologic time scales are well-expressed in the geology and landforms of the Albuquerque area. Albuquerque lies in one of the few continental rifts worldwide, and it is near the juxtaposition of four major physiographic provinces. This unique setting, coupled with outstanding and nearly complete exposures of Phanerozoic rocks, make the Albuquerque area well-suited to unraveling the Phanerozoic geologic history of north-central New Mexico. The Proterozoic assembly of North America sets the stage for later geologic events by imposing both northeast- and northwest-trending structural grains in the crust. North-central New Mexico stood relatively high during the early Paleozoic, but beginning in the Mississippian the Albuquerque area was the site of nearly continuous sedimentary deposition reflecting both proximal and distal tectonic events. The major orogenies/deformational events to affect the Albuquerque area were the ancestral Rocky Mountain orogeny (Pennsylvanian–Early Permian), the Laramide orogeny (Late Cretaceous–Eocene), and Basin and Range extension leading to formation of the Rio Grande rift (Neogene–Quaternary). In addition to these orogenic events, there have been several periods of volcanism as well as epeirogenic deformation, including late Cenozoic uplift of the southern Rocky Mountains. Our reconstruction of the geology of the Albuquerque area has identified several unanswered questions that are addressed by separate papers in this guidebook. These questions include revisiting the amount of dextral offset in the rift produced during the Laramide orogeny, the degree of rift-flank uplift that could be attributed to the flexural isostatic response of footwall unloading, and understanding syn-rift stratigraphy in terms of its hydrologic resources.

INTRODUCTION

The 50th annual New Mexico Geological Society Fall Conference returns to the Albuquerque area (Figs. 1, 2). Our thoughts on the geologic evolution of this physiographically and geologically diverse part of New Mexico have been colored by an explosion of knowledge and new data in the almost two decades since the last Albuquerque field conference. Four major physiographic provinces—the Basin and Range (Rio Grande rift), Colorado Plateau, Southern Rocky Mountains, and Great Plains, and two linear trends of volcanic rocks, the Jemez and Ortiz lineaments, are all within 100 km of Albuquerque. The diverse suite of landscapes, rocks, and structures exposed in the area of this field conference record three major episodes of Phanerozoic deformation—the late Paleozoic ancestral Rocky Mountain orogeny, Late Cretaceous–Paleogene Laramide orogeny, and mid-to-late Cenozoic extensional tectonism, which were superimposed on and influenced by a long and complicated history of Proterozoic continental assembly.

Our goals in this paper are to provide a coherent summary and reconciliation of the most current thoughts on the geologic evolution of the Albuquerque area. We focus on the Phanerozoic history of the region because it closely follows the theme for the First Day Road Log. An attempt has been made to restrict our summary to those topics that are not covered in detail by articles elsewhere in the guidebook. This integrated geologic history of the Albuquerque area defines the extent and limitations of its natural resources, most importantly water, which will play a key role in the growth and prosperity of the largest population center in the State of New Mexico.

GENERAL TIME LINE OF KEY EVENTS IN THE GEOLOGIC EVOLUTION OF THE ALBUQUERQUE AREA

We present a brief summary of key events in the geologic evolution of the Albuquerque area (Fig. 3). The Precambrian basement of the Albuquerque area is composed of mid-crustal igneous and metamorphic rocks that record a period of continental accretion and growth during the middle Proterozoic (~1.8–1.65 Ga) (Karlstrom et al., this volume). A dominant structural grain inherited from this accretion strikes northeast and coincides with modern identifiable geologic or geophysical features such as the Tijeras-Cañoncito fault zone and the Jemez lineament (Figs. 1, 2). Another structural grain strikes northwest and may have had an important influence on the architecture of local rift basins. An important widespread thermal event at about 1.4 Ga produced intrusions of granitic batholiths into the newly accreted terranes. The Sandia Granite well exemplifies this plutonism.

Our knowledge of local early Paleozoic geology and tectonic events is not well understood, given that rocks of this age are not preserved in the Albuquerque area. It is generally held that the region was a structurally elevated part of the trans-continental arch and the western passive continental margin. Beginning in the late Paleozoic, major basin subsidence and basement-cored uplifts heralded the onset of ancestral Rocky Mountain deformation. Although specific structures associated with this orogeny are difficult to identify, due in part to subsequent tectonic overprinting, the sedimentary record of rock uplift and exhumation is well preserved.

The Mesozoic Era began with a waning of tectonic activity at the end of ancestral Rocky Mountain deformation and the beginning of a protracted period of slow epeirogenic lithospheric movements as the region was covered by thin blankets of continental and marine deposits. Provenance alternated between the stable craton to the east and the active margin to the west, which was coming under increasing influence of crustal shortening and thickening associated with subduction of oceanic lithosphere and perhaps terrane accretion. By the early Late Cretaceous, the Albuquerque area experienced major subsidence and transgression of the Western Interior seaway. Compressional tectonics, formerly restricted to the active plate margin well to the west of Albuquerque, extended eastward to the hinterland, and during the Late Cretaceous–Eocene broadly uplifted the Albuquerque area. This tectonic episode is called the Laramide orogeny, and the crustal shortening associated with it was expressed as thick-skinned basement-cored uplifts, subsidence of intervening syn-orogenic basins, and northward translation and attending clockwise rotation of the Colorado Plateau resulting in a highly debated component of dextral oblique-slip movement on faults (Kelley, 1955; Chapin and Cather, 1981; Karlstrom and Daniel, 1993; Woodward et al., 1997, Cather, in press; Erslev, this volume).

The long-standing debate regarding the causes of the Laramide orogeny, as being related to the gradient of the subducting slab or collision of the "Baja B.C." microcontinent, is not resolved by rocks and structures exposed in the Albuquerque area. However, it is increasingly clear that the period of time between the end of the Laramide orogeny, traditionally the end of the Eocene, and initiation of major lithospheric extension associated with the Neogene Rio Grande rift, was locally marked by continued or episodic crustal shortening and perhaps,

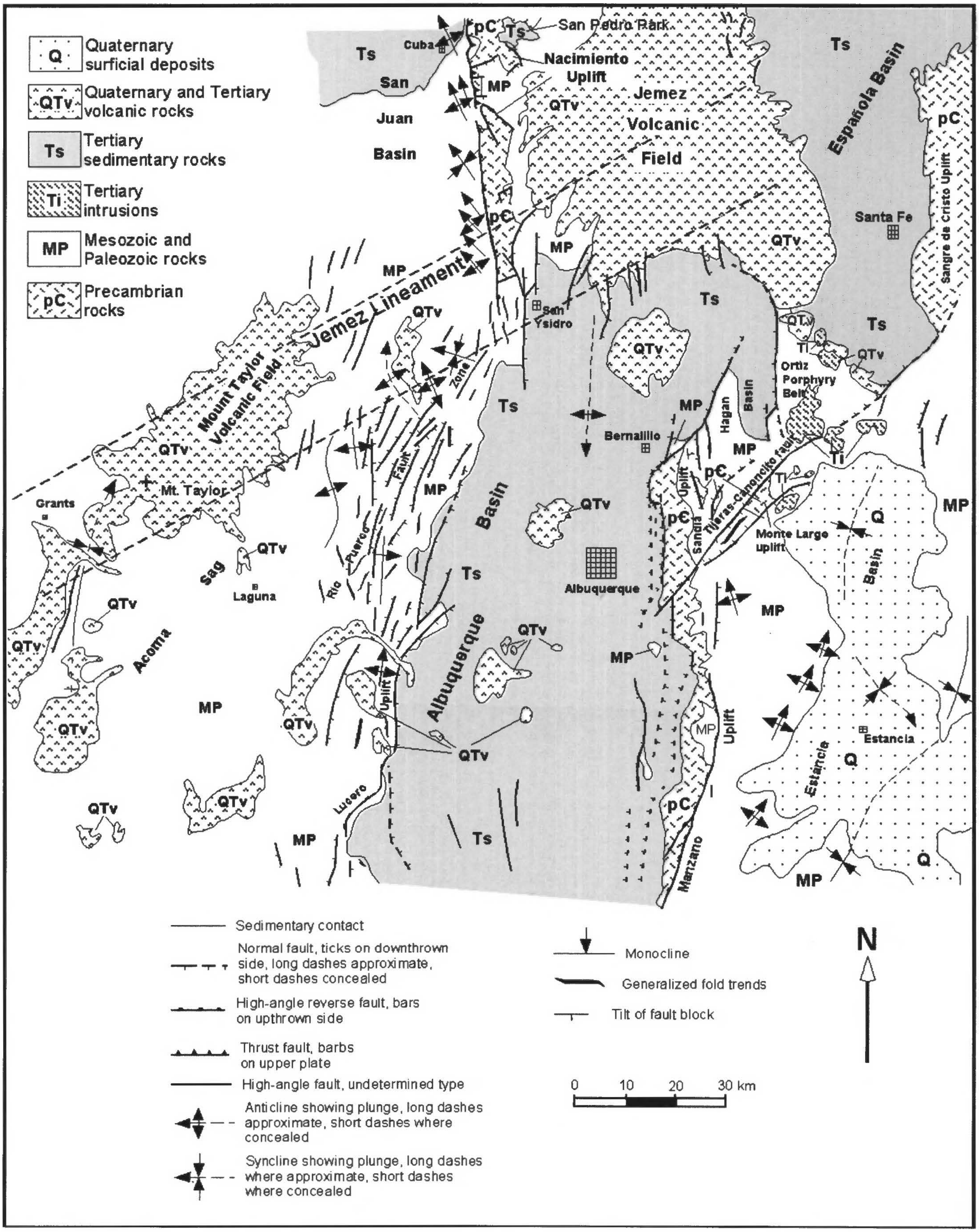

FIGURE 1. Map of the Albuquerque area showing generalized distribution of rock types and major geologic structures.

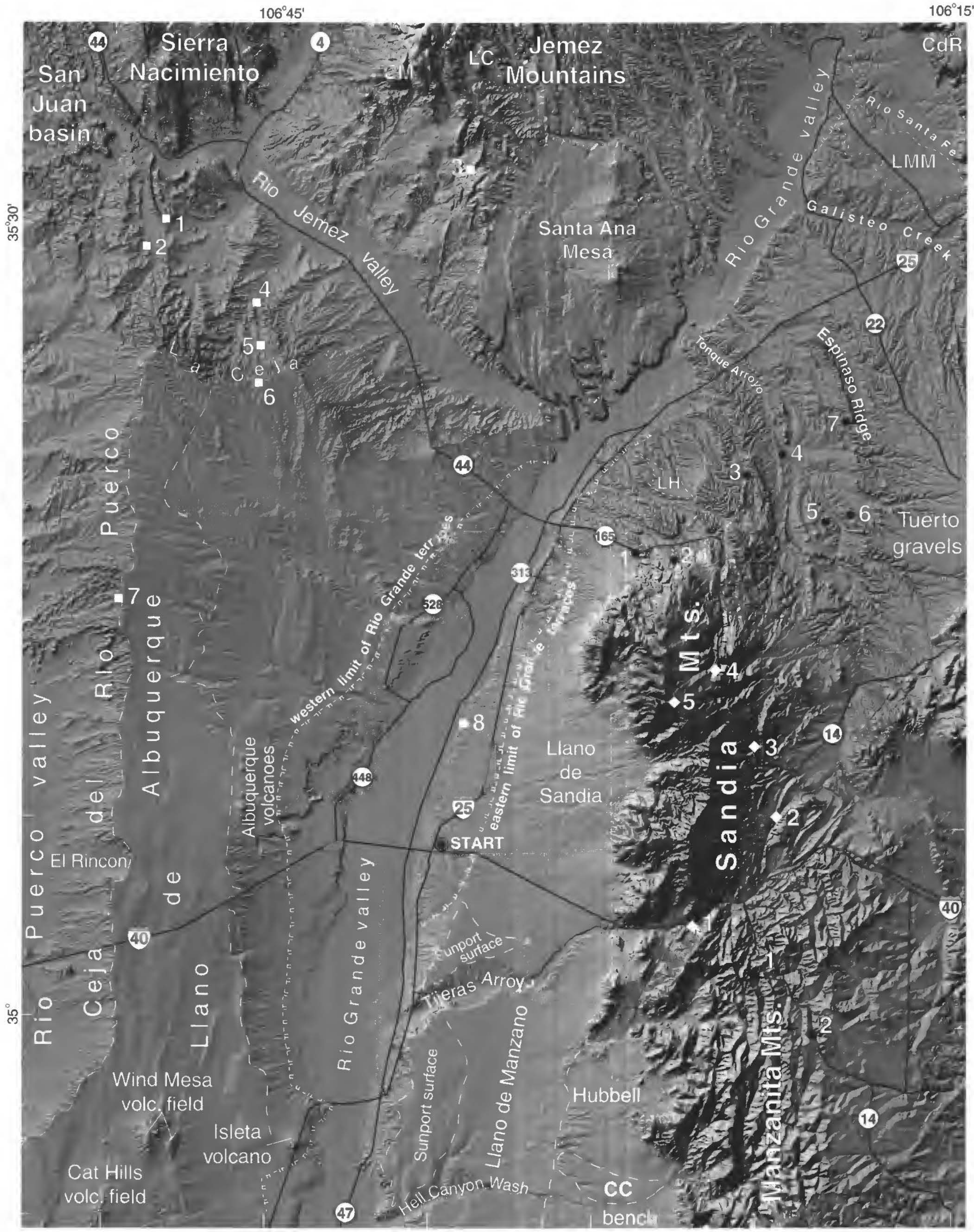

FIGURE 2. Annotated digital shaded relief map of the Albuquerque area. CM = Chamisa Mesa, LC = Loma Creston, CdR = Cerros del Rio volcanic field, LMM = La Majada Mesa, LH = Las Huertas surface, and CC = Cañada Colorada surface. Stops for the Day 1 Field Trip are represented by black dots; Day 2 Trip 1 are in white diamonds; Day 2 Trip 2 are in white squares; and Day 3 Trip 1, and in black diamonds. The Day 3 Trip 2 stops are in the Estancia basin, which is not on this image, but lies east of the Manzano Mountains.

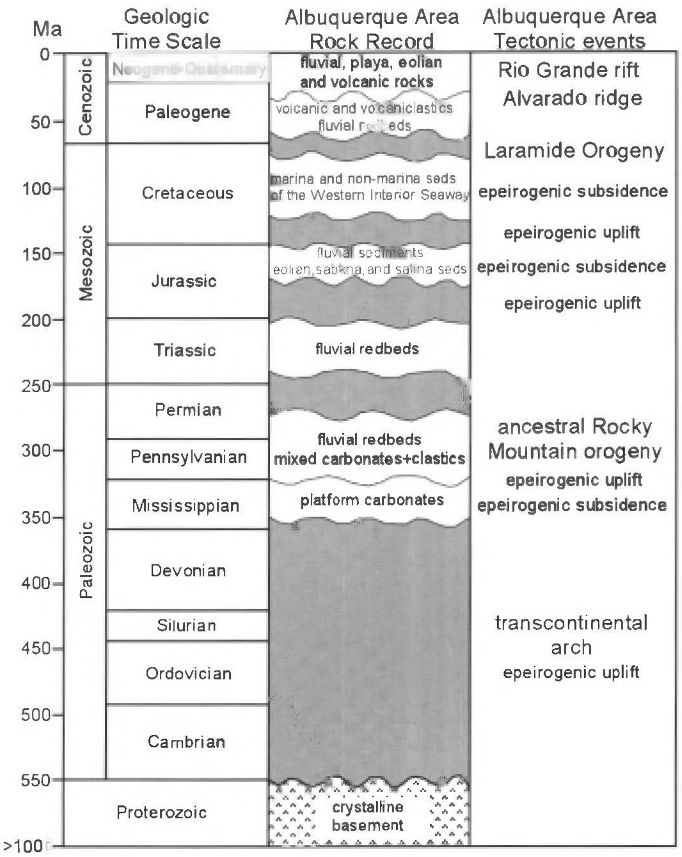

FIGURE 3. A timeline of key events in the geologic evolution of the Albuquerque area.

dextral strike-slip (Erslev, this volume).

A major thermal event closely followed the Laramide orogeny as widespread intermediate and silicic volcanism affected much of the western United States during the Oligocene "ignimbrite flare-up," a time of extensive ash-flow tuff extrusion from several caldera complexes. The Albuquerque area experienced part of this magmatic activity with the intrusion of shallow porphyries along the Ortiz lineament and lesser, poorly delineated local volcanism that is now largely masked by the Rio Grande rift.

The final major period of deformation to affect the Albuquerque area began in the Oligocene with the formation of a broad, high-standing topographic welt east of the Colorado Plateau (the Alvarado ridge of Eaton, 1986; Karlstrom et al., this volume) concurrent with the onset of major basin and range extension west of the Plateau. Collapse of the axis of this ridge in the late Oligocene and early Miocene structurally inverted the Laramide highlands and heralded the beginning of Rio Grande rift crustal extension. The rift represents a narrow zone of extended and thinned lithosphere between the relatively stable Colorado Plateau and cratonic North America. Bimodal volcanism characterizes not only the rift but the nearby northeast-trending Jemez lineament.

GENERAL GEOPHYSICAL SETTING

Magnetic map

The existence and distribution of modest- to low-amplitude magnetic anomalies within the Albuquerque area have been well known for almost two decades (Zietz, 1982; Cordell and Keller, 1984; Plate A). In particular, it has long been recognized that magnetic highs, coincident with mafic Precambrian rocks, and magnetic lows, coincident with thick sequences of Precambrian Ortega Quartzite, are dextrally offset ~145 km across the Jemez lineament (Cordell and Keller, 1984). Offset of these magnetic anomalies has been used to interpret and support as much as 150 km of cumulative dextral deformation along north–south oriented faults within the area of the Albuquerque basin since the Proterozoic (Chapin, 1983; Karlstrom and Daniel, 1993).

Bouguer and isostatic gravity maps

Bouguer gravity anomalies for the Albuquerque area are strongly influenced by rock-density distributions and closely reflect crustal structure below about 10 km (Plate C). For example, the gravity lows generally coincide with rift basins filled with low-density sediments, and the highs correspond to the rift flanks.

The Bouguer gravity data support an asymmetry to the Albuquerque basin with more subsidence present along its eastern margin. However, northeast-trending structures, such as the Tijeras-Cañoncito fault zone (Fig. 1) are not well represented by the gravity data (Plate B). Rather, there are several northwest-trending gravity highs across the Albuquerque basin, not expressed in the aeromagnetic data (Plates A, B) that may coincide with exposed structures such as the La Cueva fault (Kelley and Northrop, 1975). The gravity data are used in an inverse model of the flexural rigidity of the lithosphere and degree of rift flank uplift that could be attributed to rift extension (Roy et al., this volume).

The isostatic residual gravity map is a de-trended version of the Bouguer map (Plate D); it reflects shallow crustal structures less than 10 km in depth (Daggert et al., 1986). In general, this map shows similar basement structures seen in the Bouguer gravity map. An important feature of the isostatic map is the location of the rift-bounding fault(s) on the eastern flank of the Albuquerque basin. The gravity data indicate that the fault(s) with significant structural offset do not coincide with the Sandia mountain front, nor is this structure in the middle of the basin along the proposed location of the Rio Grande fault (Russell and Snelson, 1994).

Crustal thickness

Recent maps of crustal thickness throughout the western United States (Sheehan et al., 1995; Das and Nolet, 1998; Fig. 4) have been produced from inversion of seismic wave velocity. The most obvious features of these maps are the broad region of overthickened crust (up to 50 km) that underlies the southern Rocky Mountains and extends eastward beneath the High Plains, the thinned crust (~25–35 km) that underlies the Basin and Range, and the crust of intermediate thickness (~40 km) that roughly coincides with the Colorado Plateau. Crustal thickness for the Albuquerque area is about 40 km.

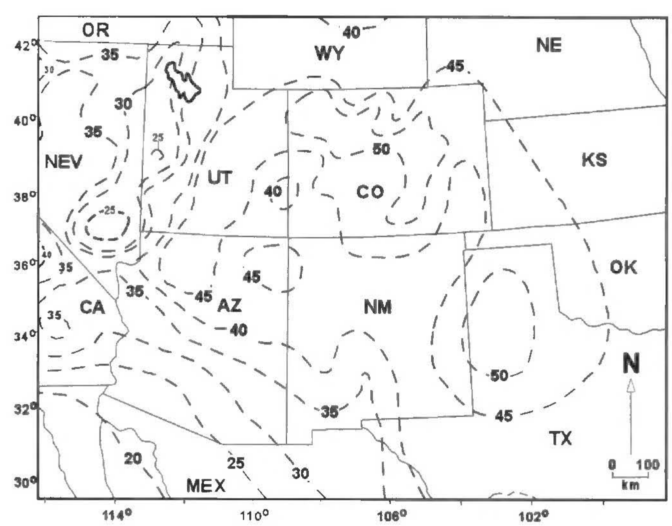

FIGURE 4. Contour map of crustal thickness for the southwestern United States. Thicknesses determined by inversion of seismic wave velocities (modified from Sheehan et al., 1995, and Das and Nolet, 1998).

Buoyant mantle

The Rio Grande rift stands higher in mean elevation than the adjacent Colorado Plateau and High Plains (Cordell, 1978; Eaton, 1986; Roy et al., this volume; Fig. 5). The general topographic form of the rift is remarkably similar to a divergent plate boundary, and although we do not allude to this as the origin of the rift, it is probably a reflection of the mantle thermal structure beneath the rift. Recent maps of upper mantle velocity in the western United States (Humphreys and Dueker, 1994; Dueker, unpublished data) can be interpreted in terms of the respective mantle thermal structure (Bridwell, 1978; Clarkson and Reiter, 1984; Decker, et al., 1984) and its buoyant effect on the overlying crust. Even a cursory glance at the distribution of the low-velocity upper mantle reveals a strong correlation with regions of high-standing topography (Roy et al., this volume; Plate E). In particular, the Jemez lineament and Rio Grande rift are regions underlain by buoyant mantle. Broad epeirogenic deformation of the Albuquerque area suggested by regional exhumation of Laramide uplifts and the adjacent High Plains (Karlstrom et al., this volume) during the middle–late Cenozoic may be related to interaction of this buoyant mantle with the base of the lithosphere.

CAMBRIAN TO MISSISSIPPIAN TIME

Our reconstruction of the geologic history of the Albuquerque area begins in the Paleozoic. From Cambrian through Devonian time, the Albuquerque region was located on the southern flank of the transcontinental arch, an elevated region along the western passive continental margin (Lochman-Balk, 1972). There are no lower Paleozoic strata in this region; however, in southern New Mexico, Cambrian through Devonian strata have a composite stratigraphic thickness of about 1000 m (Kottlowski, 1963; Woodward and DuChene, 1981).

Distinctive brick-red syenite of probable Ordovician or possible Cambrian age is present in the southern part of the Nacimiento uplift (Woodward, 1987). Similar rocks in the Pedernal Hills and Lobo Hill east of Albuquerque yielded a whole-rock Rb-Sr isochron age determination of about 469 ± 7 Ma, with maximum possible ages of 496 and 604 Ma for the two occurrences (Loring and Armstrong, 1980). A new

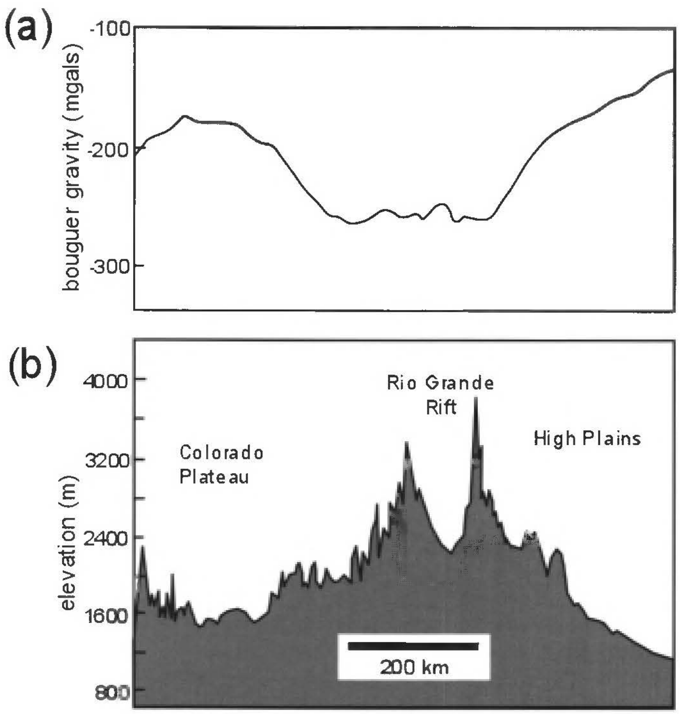

FIGURE 5. West-to-east cross section from the Colorado Plateau to High Plains along the Colorado-New Mexico border showing: (**a**) the Bouguer gravity anomaly and (**b**) high mean elevation of the rift (modified from Cordell, 1978).

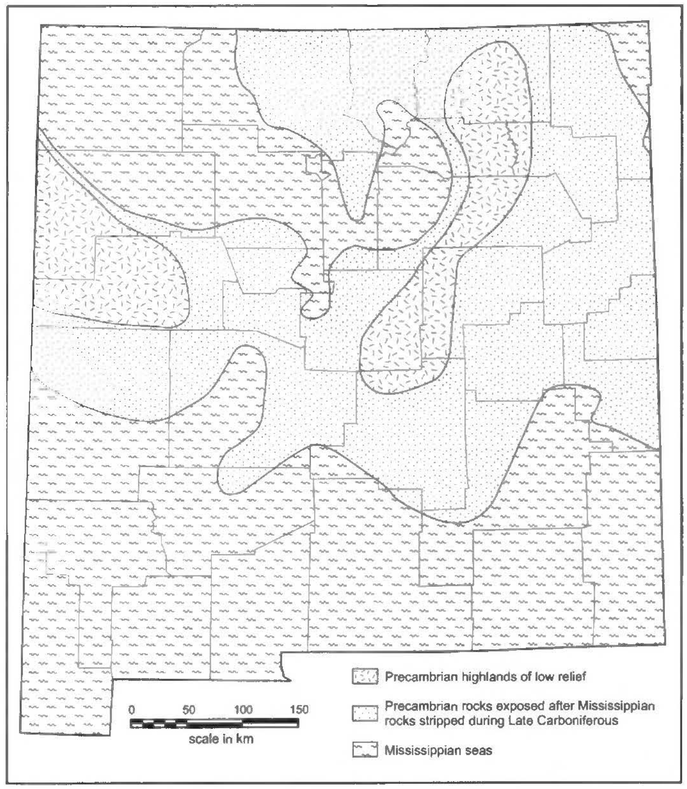

FIGURE 6. Simplified paleogeographic map of New Mexico during the Mississippian (after Armstrong et al., 1979). Precambrian rocks exposed in western New Mexico are part of the emergent Zuni highlands. Precambrian rocks exposed in east-central New Mexico are part of the emergent Pedernal highlands.

$^{40}Ar/^{39}Ar$ biotite-plateau date of 518 ± 5.7 Ma records the emplacement of an associated monzonite (McLemore et al., this volume). This alkalic igneous activity ranged from southern Colorado to perhaps south-central New Mexico. Dike orientation suggests NNE–SSW extension during magmatism, perhaps associated with an aulacogen in southern Oklahoma (Loring and Armstrong, 1980; McLemore et al., this volume).

The oldest preserved Paleozoic rocks in the Albuquerque area are Mississippian strata of the Arroyo Peñasco Group (Plate F). These rocks nonconformably overlie Precambrian basement and represent a marine transgression into north-central New Mexico (Armstrong and Mamet, 1979). The strata consist of a thin basal sandstone (Del Padre Sandstone) overlain by a thin (<30 m thick) succession of shallow-water carbonates. The Arroyo Peñasco Group was deposited in a shallow sea between two major emergent areas in central New Mexico, the Zuni highlands to the west and the Pedernal highland to the east (Armstrong and Holcomb, 1989; Fig. 6). Strata of the Arroyo Peñasco Group are preserved only in restricted low-standing regions or regions downwarped prior to a period of widespread erosion that removed these rocks from higher, intervening areas prior to the deposition of Pennsylvanian strata (Armstrong et al., 1979; Fig. 6). The tectonic activity that resulted in local erosion of the Arroyo Peñasco Group is not well understood, as it falls between the Late Devonian Antler Orogeny and the Pennsylvanian–Permian ancestral Rocky Mountain orogeny (Armstrong and Mamet, 1974), although there is evidence in Colorado for the onset of ancestral Rocky Mountain deformation as early as the Mississippian.

The Arroyo Peñasco Group is overlain by the Log Springs Formation of inferred Late Mississippian age (Armstrong and Mamet, 1979). This unit consists of fine-grained red beds (mostly siltstone) derived from uplifted and weathered carbonates. The Log Springs Formation may also represent a paleosol, as it is locally preserved in a paleokarst in the top of the Arroyo Peñasco Group.

LATE PALEOZOIC ANCESTRAL ROCKY MOUNTAINS

Major tectonic upheavals in the late Paleozoic (Plate G) followed the relatively minor tectonic activity of the earlier Paleozoic. Late Paleozoic deformation produced north- to west-trending elongate basins and adjacent basement-cored uplifts in New Mexico, Colorado (Fig. 7), Oklahoma, Texas, Arizona, and Utah. Basement uplift and basin subsidence began in latest Mississippian or Early Pennsylvanian time and ended in the Early Permian. Those uplifts in New Mexico, Colorado, eastern Utah, and northeastern Arizona have been referred to as the ancestral Rocky Mountains (Lee, 1918; Eardley, 1951), and the episode of tectonism thus has been called the ancestral Rocky Mountain (ARM) orogeny.

Thicknesses and rock-types of Pennsylvanian and Permian strata provide the bulk of the data for interpreting the paleotectonics of the ancestral Rocky Mountains. Uplift-bounding faults have been difficult to identify because they are buried or may have been reactivated during younger deformation. However, several studies have documented ancestral Rocky mountain faults (Fig. 7), including the Anadarko region of southern Oklahoma where the basement uplift has been thrust over the adjacent basin (reviewed in Ye et al., 1996), the compressional and transpressional structures in the Paradox basin and Uncompahgre uplift (Baars and Stevenson, 1982), the Pecos-Picuris fault along the west side of the Taos trough, faults in the Joyita Hills (Beck and Chapin, 1994), faults in the Manzanita Mountains (Karlstrom et al., 1998), a dextral strike-slip fault in Sierra Nacimiento (Pollock et al., 1998), and the fault-bounded east side of the Estancia basin (Barrow and Keller, 1994).

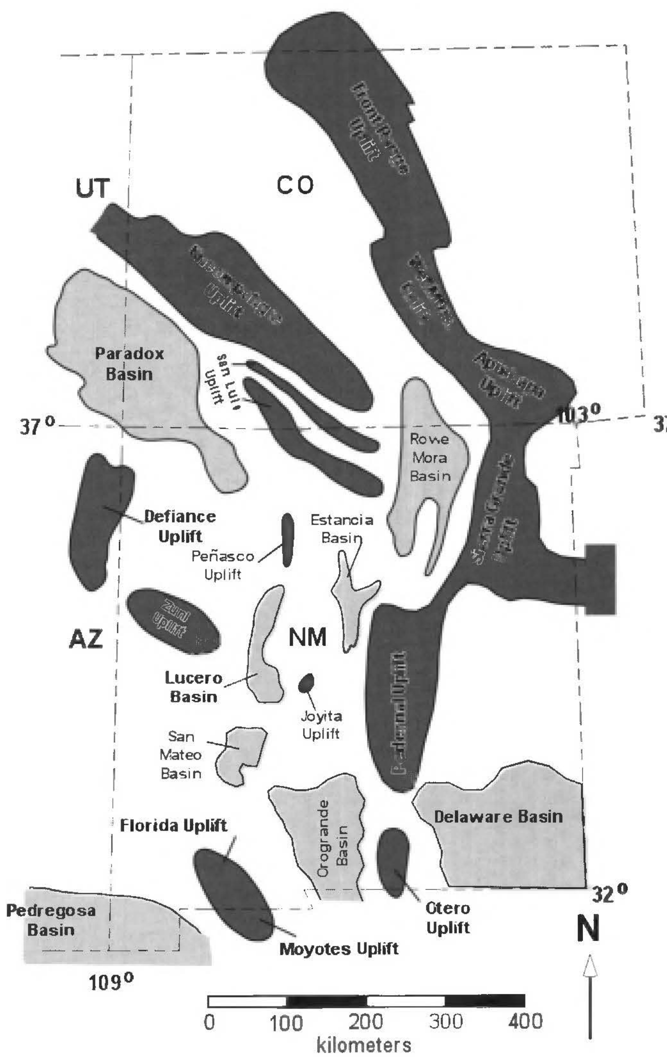

FIGURE 7. Ancestral Rocky Mountain uplifts and basins (modified from Baars and Stevenson, 1984; Baars, 1988).

Sedimentation in regions proximal to ARM uplifts consisted of coarse-grained siliciclastic and mixed carbonate-clastic facies. Compositionally, most late Paleozoic sandstones are characteristically feldspathic. Basin interiors initially received thick accumulations of dominantly carbonate rocks, which grade upward into clastic-rich facies. Toward the end of ARM deformation, a broad clastic wedge of fluvial redbeds of the Abo Formation blanketed the Albuquerque area and most of New Mexico (Fig. 8).

Ancestral Rocky Mountain uplifts

Peñasco uplift

Although only the Peñasco uplift is present in the area of this year's field conference, several other uplifts are also described below, as a regional tectonic analysis of the late Paleozoic involves out of necessity discussion of all of northern New Mexico. The Peñasco uplift was a north-trending basement block about 62-km long and as much as 10-km wide that approximately coincides with the present Sierra Nacimiento (Fig. 7). It is bounded on its western flank by a system of north-striking faults that show about 15 km of right-lateral offset of magnetic anomalies (Plate A). One of these faults has been determined to have ~6–18 km of ARM dextral strike-slip offset determined from crude piercing lines reconstructed for offset Precambrian rock-types (Pollock et al., 1998). It is estimated that between ~5 km (Baltz, 1967; Woodward et al., 1997) and ~20–33 km (Cather, in press) of any additional dextral offset is post-late Paleozoic in age. Rise of the uplift began during deposition of Middle Pennsylvanian beds that appear to thin depositionally toward and are absent along the axis of the uplift. Principal orogenic rise of the uplift is recorded by coarse clasts of Precambrian rocks in Middle and Upper Pennsylvanian strata, including arkosic and (or) conglomeratic beds, becoming more abundant and thicker upsection. A

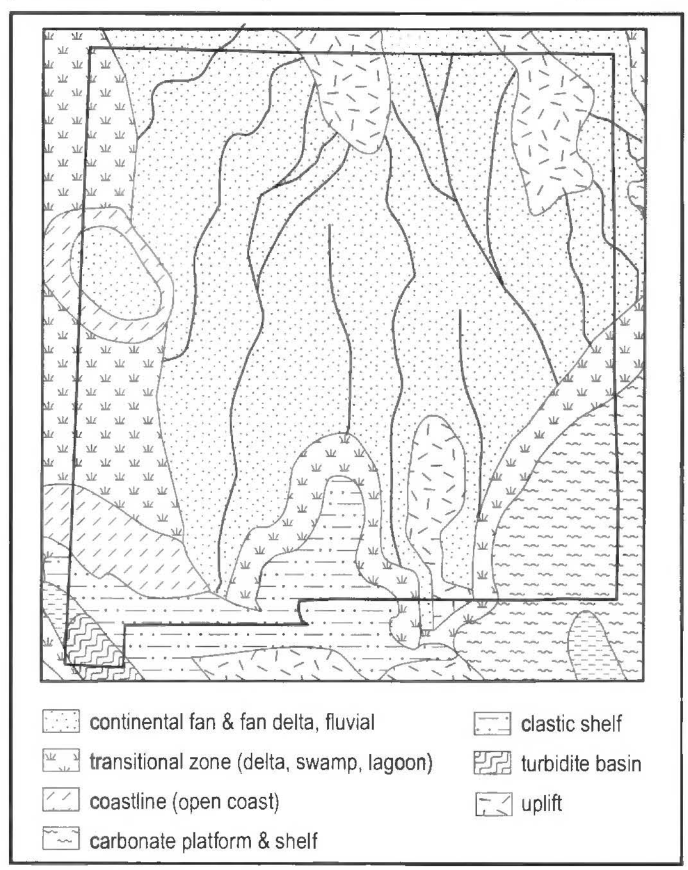

FIGURE 8. Generalized paleogeography of New Mexico during Abo Formation (Early Permian, Wolfcampian) deposition.

conglomeratic facies of the Pennsylvanian Madera Group, including boulders, near the southwestern margin of the Sierra Nacimiento is interpreted to indicate the presence of a syn-depositional fault with a steep scarp on the western side of the Peñasco uplift. About 5 km-east of this locality, the Madera Group is markedly finer grained, suggesting that the Peñasco uplift was asymmetric, with a gentler slope on the east side, consistent with an east-tilted fault block (Martinez, 1974). Terrestrial strata of Early Permian age appear to thin locally across the uplift, suggesting that the uplift remained high standing prior to being overtopped by aggrading continental deposits.

Uncompahgre uplift

The northwest-trending Uncompahgre uplift of west-central Colorado is at least 500-km long and as much as 100-km wide (Fig. 7). The Uncompahgre uplift began to rise in the Early Pennsylvanian, and by the Middle Pennsylvanian crystalline rocks were being eroded, and coarse clasts were deposited in the adjacent part of the Paradox basin. Sedimentation continued until the earliest Permian, when erosion of the uplift filled the basin with fluvial red beds (Baars, 1988). The Uncompahgre uplift is interpreted as a basement-uplift thrust to the southwest over the adjacent Paradox basin (Baars and Stevenson, 1982). Wells in the Paradox basin penetrate overturned Paleozoic strata beneath Precambrian rocks (Stevenson and Baars, 1986). Baars and Stevenson (1982) suggest this zone of thrusts was a major right-slip zone containing flower structures with southwest-verging thrusts and reverse faults. Their interpretation of right-slip appears to be based on the assumption that there was regional north-south compression prior to the Mesozoic. Soegaard (1990) inferred that the northeastern side of the Uncompahgre uplift was bounded by a southwest-dipping system of thrust faults; definitive structural data are lacking due to Laramide deformation and cover by younger rocks. As much as 7600 m of structural relief is present between the deepest part of the Paradox basin and the Uncompahgre uplift (Stevenson and Baars, 1986). The basin is asymmetric, being deeper near the uplift where the Pennsylvanian strata are at least 1900-m thick (Stevenson and Baars, 1986).

San Luis uplift

The San Luis uplift has generally been considered to be a southeastern extension of the Uncompahgre uplift (Fig. 7), but Baars and Stevenson (1984) presented lithologic and stratigraphic data for Pennsylvanian rocks suggesting that the San Luis uplift is a separate, fault-bounded ARM range. The San Luis uplift was initiated in the Middle Pennsylvanian and was buried by Lower Permian arkosic beds derived from the Uncompahgre uplift (Baars and Stevenson, 1984).

Joyita uplift

The Joyita uplift is northerly trending, about 16-km long and 10-km wide (Read and Wood, 1947); Fig. 7). Thin sequences of Pennsylvanian strata, locally present in the uplift (Kottlowski and Stewart, 1970), thicken to as much as 820 m in adjacent areas (Beck and Chapin, 1994). Upper Pennsylvanian (Virgilian) strata were deposited on the uplift, but were eroded during the Late Pennsylvanian or Early Permian (Kottlowski and Stewart, 1970). The dominant episode of uplift was probably in the Early Permian. Well-documented, north-trending, high-angle normal faults, some with sinistral kinematic indicators, are present (Beck and Chapin, 1994). A north-striking syn-depositional growth fault on the western side of the uplift dips steeply to the west and appears to be superimposed on a mylonite zone of inferred Proterozoic age (Beck and Chapin, 1994). Northwest-striking faults also with an ARM origin, are noted to have undergone late Cenozoic movement (Beck and Chapin, 1994). The Joyita and Peñasco uplifts may be connected by a north-trending structurally positive axis underlying the Neogene sedimentary fill of the Rio Grande rift (Read and Wood, 1947; Baars, 1982).

Pedernal uplift

The north-trending Pedernal uplift of central New Mexico is about 248-km long and 96-km wide (Fig. 7). The northern part of the uplift is bounded on the west by the Estancia basin and on the east by the Delaware basin. The western side of the northern part of the uplift was marked by a buried, geophysically imaged, north-striking, high-angle fault zone characterized by negative flower structures (Barrow and Keller, 1994) that formed during the Pennsylvanian. This fault separates a sedimentary sequence at least 1000-m thick on the west from a thinner sequence to the east. A strike-slip component of movement on this fault zone, inferred to be sinistral to explain the general basin geometry but lacking any kinematic data, has been proposed (Barrow and Keller, 1994).

The structural setting of the eastern side of the uplift is more ambiguous. Kelley (1972) argues for onlapping Permian strata with no indications of a fault-bounded margin, suggesting instead eastward tilt of the uplift. Precambrian rocks in the northern part of the uplift are overlain by Lower–Middle Permian (Leonardian–Guadalupian) strata, indicating that the uplift was still emergent during the Early Permian (Kelley, 1972). New results (Broadhead, in prep.) may support deep, narrow basins on the east side of the uplift, similar to those demonstrated for the west side.

Tectonic models for ancestral Rocky Mountain deformation

Two principal models account for the ancestral Rocky Mountain orogeny. Kluth and Coney (1981) proposed that deformation was a response to northwest–southeast crustal shortening caused by the collision of North America with South America-Africa to produce the Ouachita-Marathon orogeny (Fig. 9a). Until recently, this was the prevailing model and it appears to be supported by limited kinematic indicators on ARM faults. Recently, Ye et al. (1996) presented contrasting evidence for ARM deformation with a model of northeast–southwest crustal shortening driven by a northeast-dipping subduction boundary along the southwest side of North America (Fig. 9b). Following the well-accepted work of Kluth and Coney (1981), many workers in New Mexico assumed that north-striking faults of late Paleozoic age underwent left slip because this was consistent with the model of northwest–southeast crustal shortening with respect to the orientation of the Ouachita-Marathon fold belt (e.g., Karlstrom and Daniel, 1993; Fig. 9a). Woodward et al. (this volume) challenge the traditional notion that ancestral Rocky Mountain deformation was characterized by left slip only. They suggest right slip in the context of the model proposed by Ye et al (1996), which does have some limited kinematic support such as the dextral ARM fault in Sierra Nacimiento (Pollock et al. 1998). Such a reevaluation of ARM deformation may have important consequences for the origin of well-documented post-Paleozoic dextral offset throughout central New Mexico.

MIDDLE PERMIAN–LATE CRETACEOUS

During the time period between the Early Permian and Late Cretaceous, a span of more than 200 m.y., the Albuquerque area was marked by a protracted period of relative tectonic quiescence. Sedimentation occurred, but tectonism providing a source for it took place well outside of the region. The Middle Permian–Late Cretaceous record is therefore strongly biased towards times of regional subsidence to accommodate and preserve sediments.

The ancestral Rocky Mountain orogeny ceased by late Early Permian (Leonardian) time. During the late Leonardian (Plates H, K), two transgressions left relatively thin blankets of predominantly marine sediments (part of the Yeso Formation and the intertongued Glorieta and San Andres formations) in north-central New Mexico. Following deposition of these rocks, New Mexico entered a period where it stood relatively high for ~40 m.y., through the Middle and Late Permian and the Early Triassic. With little or no subsidence in north-central New Mexico during this interval, no sediments of this age are preserved there. Deposition resumed with the accumulation of Middle Triassic (Moenkopi Formation) and Upper Triassic (Chinle Group) (Plates I, L) fluvial red beds across northern New Mexico (Lucas, 1995). These sediments were sourced from the south and southeast by large rivers, some

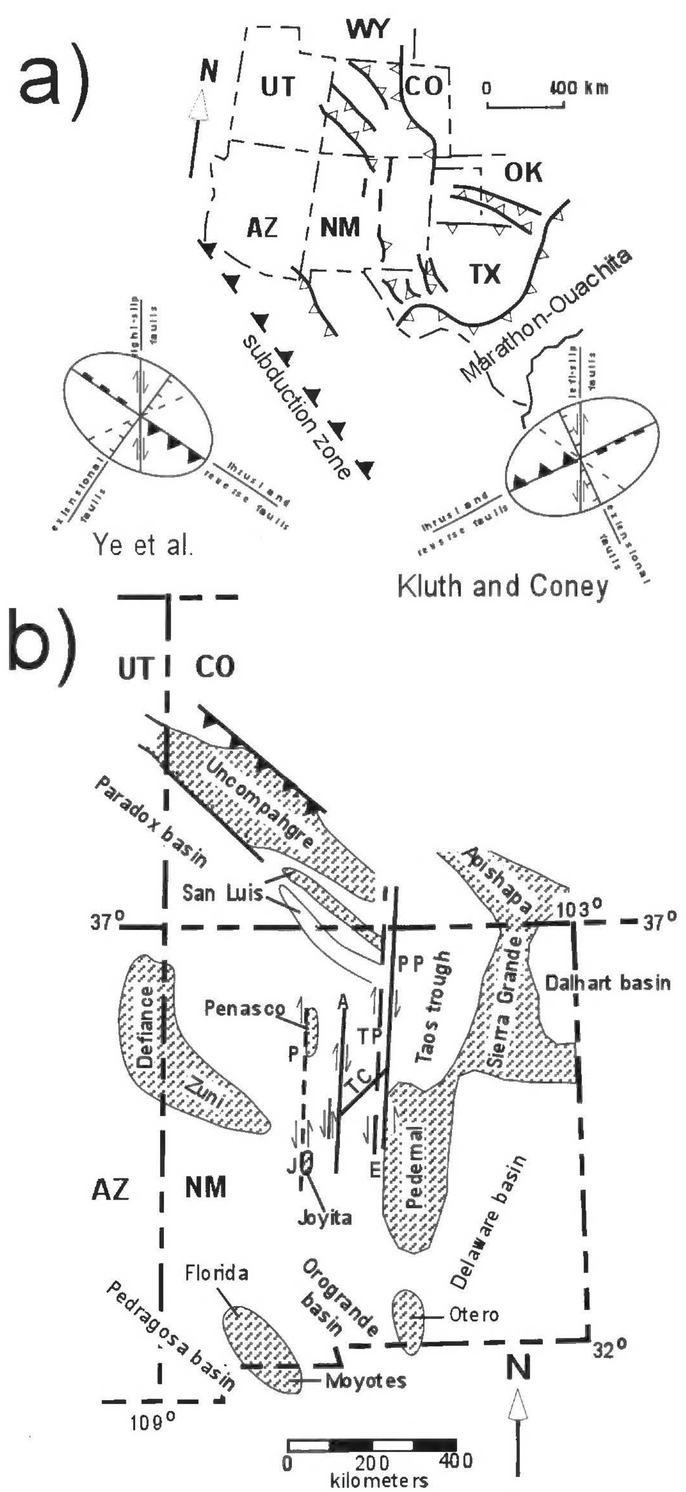

FIGURE 9. Models of ancestral Rocky Mountain deformation from Kluth and Coney (1981), and Ye et al. (1996). (**a**) Note sinistral slip on north-striking faults for the Kluth and Coney model and dextral slip on north-striking faults for the Ye et al. model. (**b**) Modification of the Ye et al. (1996) in the context of ARM features in New Mexico. P = Peñasco fault (Pollack et al., 1998), A = Albuquerque fault, J = Joyita fault (Beck and Chapin, 1994), E = Estancia fault (Barrow and Keller, 1994), TC = Tijeras-Cañoncito fault, TP = Tusas-Picuris fault, PP = Pecos-Picuris fault. Offset for TP, PP, and A faults are based on offset magnetic anomalies only.

the scale of the modern Mississippi River, draining the northern rift shoulder of the opening Gulf of Mexico (McGowen et al., 1983; Riggs et al., 1996). Uplift of that rift shoulder marked the initial phases of extensional tectonism to fragment the Pangean supercontinent and eventually open the Atlantic Ocean basin. During the same time interval, the western convergent margin of Pangea, well west of New Mexico, was a complex subduction arc-trench system. By the Late Triassic, the arc was migrating eastward, well outboard of the craton, though probably already fused along its southern terminus, making it a peninsula with a back-arc marine basin separating it from the foreland (Stanley et al., 1971; Monger et al., 1972; Dickinson, 1976).

Upper Triassic rocks are unconformably overlain by Middle Jurassic strata of the San Rafael Group in the Albuquerque area. The unconformity between these rocks represents another approximately 40-m.y. hiatus. At the beginning of the Middle Jurassic much of the southwestern United States, including the Albuquerque area, was covered by a vast sand sea (the Entrada erg). These arid lands were south and southeast of the Curtis-Sundance seaway that filled the back-arc basin east of the eastwardly migrating arc. Deposition after the Entrada Formation (upper San Rafael Group) occurred in ergs, sabkhas, tidal flats, and salinas across a relatively tectonically quiet Albuquerque area influenced largely by eustatic sea-level changes and related regional climatic changes. Rapid northward movement of the North American plate, which until this time had been in an equatorial position, brought the Albuquerque region through the arid low-middle latitudes to the humid middle latitudes and into the zone of prevailing westerlies by the beginning of the Late Jurassic (Plates J, M).

In Late Jurassic time, tectonic events west of New Mexico began to increasingly influence sedimentation in the Albuquerque area. The volcanic arc had migrated eastward and collided with the craton, initiating the Sevier orogeny. Crustal thickening at the continental margin formed a foreland fold and thrust-belt, principally in western Utah. Related to this foreland basin was a huge lithosphere sag of poorly understood origin that extended from Alberta to New Mexico and from central Utah to western Kansas (Dickinson, 1976). Fluvial sedimentation in this broad sag was initiated by rivers flowing dominantly eastward, and later northward, that deposited the Morrison Formation, which blankets all of northern New Mexico (Anderson and Lucas, 1997; Lucas and Anderson, 1998).

Another hiatus followed in north-central New Mexico at the close of Morrison Formation deposition. There are essentially no Lower Cretaceous strata preserved, indicating a hiatus of ~50 m.y. The youngest member of the Morrison Formation, the Jackpile Sandstone, is a deeply weathered kaolinite-rich quartz sandstone. The pronounced chemically weathered characteristics of this unit are consistent with a protracted period of subaerial exposure. During the Early Cretaceous, continued shortening and crustal thickening to the west resulted in the shedding of a thick sedimentary prism in a deepened and enlarged foreland basin in Utah. The eastern feather edge of that basin extended eastward into the Chama area of New Mexico, where fluvial strata of the Cedar Mountain (Burro Canyon) Formation are preserved (Saucier, 1974).

Sedimentation resumed in the Albuquerque area with an east-to-west marine transgression of the Western Interior Seaway during the early Late Cretaceous (Plates N, Q). Similar in extent to the Morrison Formation basin of the Late Jurassic, but greater in depth, the origin of this broad lithosphere sag is not well understood. It has been suggested that it is a reflection of epeirogenic subsidence driven by dynamic mantle topography (Burgess et al., 1997). In any event, the combination of widespread subsidence and high eustatic conditions brought an epeiric seaway across the Albuquerque area that would persist throughout the Late Cretaceous. The Dakota Formation, which unconformably overlies the Morrison Formation, records the initial transgression of this seaway. Deposition of the overlying Mancos Formation records the time of maximum transgression and also the deepest water conditions. Numerous transgressive-regressive cycles, driven by eustatic changes and relative sediment supply, ensued as rivers sourcing the Sevier highlands to the west transported sand into the seaway. Regressive sandstones increase in frequency upsection until deposition became completely fluvial by the end of the Cretaceous, heralding the final retreat

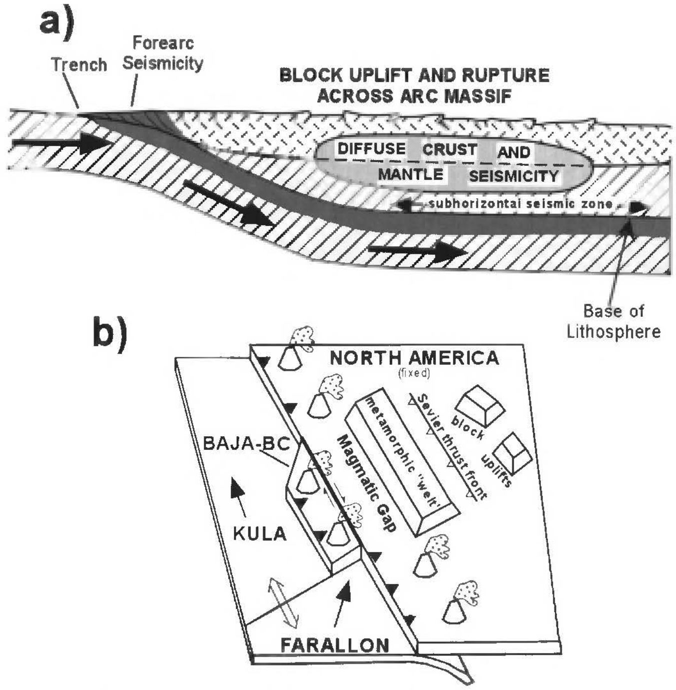

FIGURE 10. Contrasting models for Laramide deformation from (**a**) Dickinson and Snyder, (1978), and (**b**) Maxson and Tikoff (1996). In the Dickinson and Snyder model, crustal shortening in the Rocky Mountain foreland is driven by a shallowly-subducted Farallon plate. In the Maxson and Tikoff model, Laramide compression is the result of the transpressional collision "run" of the Baja BC microplate.

of the seaway to the east.

LARAMIDE OROGENY

Both the Colorado Plateau and Rocky Mountain physiographic provinces attained their present structural outlines during the Late Cretaceous–Eocene Laramide orogeny, although both have suffered subsequent deformation. Laramide deformation in north-central New Mexico was the culmination of crustal shortening and thickening that had characterized the western convergent margin of North America throughout the Mesozoic. The reasons why deformation, which had been more or less restricted to the plate margin, was translated almost 1000 km eastward into the craton are strongly debated (Fig. 10). One school of thought holds that the angle of subduction of the Farallon slab shallowed considerably, which imposed some tractive force at the base of the North American lithosphere and concomitantly translated shortening to the east (Dickinson and Snyder, 1978; Bird, 1988; Fig. 10a). The relatively flat-slab subduction for the central Andes is often cited as a modern analogue of this model of Laramide deformation. It has been pointed out that the transmittal of stresses to the base of the North American lithosphere in the flat slab model is unlikely, and a different mechanism must be called upon to explain the crustal thickening. One idea is that flat slab subduction was accompanied by the construction of a huge overthickened crustal wedge in the west (Sevier orogeny), which deformed the foreland as it grew self-similarly to the east (Livaccari, 1991). A more recent idea is that crustal shortening during Laramide time resulted from the oblique collision of a micro-continent during its translation from Baja California to Canada by dextral strike slip—the so called "Baja B.C." hypothesis (reviewed in Maxson and Tikoff, 1996) (Fig. 10b).

The Laramide orogeny (Fig. 11), and resultant crustal shortening in the Albuquerque area, were driven primarily by northeast movement of the Colorado Plateau with respect to cratonic North America. The result was a major high-standing welt between the Colorado Plateau and the future High Plains characterized by dextral oblique reverse faults (Kelley, 1955; Baltz, 1967, 1978; Woodward and Callender, 1977; Chapin and Cather, 1981). The Colorado Plateau is structurally unique insofar as it has been only moderately deformed compared to the more intensely deformed surrounding regions. Long-wavelength shallow-amplitude structural uplifts and basins are the major tectonic features of the Colorado Plateau. Most of the uplifts are bounded on one side by monoclines in Phanerozoic strata; most workers interpret the monoclines to be underlain by thrust or reverse faults rooted in Precambrian rocks (Kelley, 1955). North-trending monoclines may have a component of right shift. As an example, the Defiance monocline of eastern Arizona has a sinuous trace because of southeast-plunging cross-folds that suggest upwards of 13 km of right shift (Kelley, 1967). The principal tectonic elements of the Colorado Plateau that pertain to and are of interest to this field conference include the San Juan Basin, the Rio Puerco fault zone, and the Lucero uplift. These features are briefly described below.

Laramide uplifts and basins

San Juan Basin

Only the southeastern corner of the San Juan Basin (Figs. 1, 11) is in the area of this field conference. In plan view the basin is nearly circular and about 160 km in diameter. In cross-section it is strongly asymmetric, with the axial trace defining a concave-southward arc near the northern margin of the basin. The eastern boundary of the San Juan Basin is defined by a ~5-km-wide zone of right-shifted en echelon folds, cut by reverse and thrust faults separating it from the Nacimiento uplift, which largely coincides with the ARM Peñasco uplift. West of these faults, basin strata form a synclinal bend that is locally overturned. Laramide synorogenic sedimentary rocks of the lower Eocene San Jose Formation derived from the rising Brazos and Sangre de Cristo uplifts (Baltz, 1967; Smith, 1988, 1992), are preserved along the eastern margin of the San Juan Basin. Along the southeastern edge of the basin, there are northwest-plunging, en echelon folds that deform the Eocene strata. These folds are interpreted as evidence of dextral movement between the Colorado Plateau and the Nacimiento uplift.

Rio Puerco fault zone

The Rio Puerco fault zone is about 72-km long and 13–29-km wide (Figs. 1, 11). Three major groups of structures occur in this zone and are, from north to south, northwest-trending en echelon folds, northeast-trending en echelon normal faults, and the east-facing Ignacio-Lucero monocline (Slack and Campbell, 1976). There is a maximum of 914 m of down-to-the-east major structural relief across the fault zone. Slack and Campbell (1976) suggested that this complex geometry of the three major structures is best explained by early Cenozoic (Laramide) dextral movement along the fault zone, middle Cenozoic (post-Laramide *sensu stricto*) vertical uplift of the Ignacio-Lucero monocline, and late Cenozoic extension associated with the Rio Grande rift.

Lucero uplift

The Lucero uplift is a west-tilted fault block about 56-km long and 11–19 km wide (Figs. 1, 11). The western flank of the uplift is transitional with the Acoma sag and is marked mostly by Pennsylvanian and Permian strata dipping northwesterly at 5–15°. On the north, the uplift merges through the Lucero anticline with the Ignacio monocline of the Rio Puerco fault zone. The eastern margin of the uplift is a structurally complex zone marking the boundary between the Colorado Plateau and the Rio Grande rift (Kelley and Wood, 1946; Callender and Zilinski, 1976). Structures inferred to be of Laramide affinity along this zone are characterized by an east-facing monocline with gravity slide blocks containing a lesser thrust fault (Callender and Zilinski, 1976). Oligocene intrusions have been emplaced along some of the gravity-slide faults. Superimposed on this zone is an east-dipping high-angle normal fault with at least 3500 m of stratigraphic separation that defines the boundary between the Rio Grande rift and the uplift. Numerous small, complex folds and faults displace steeply east-dipping rocks on

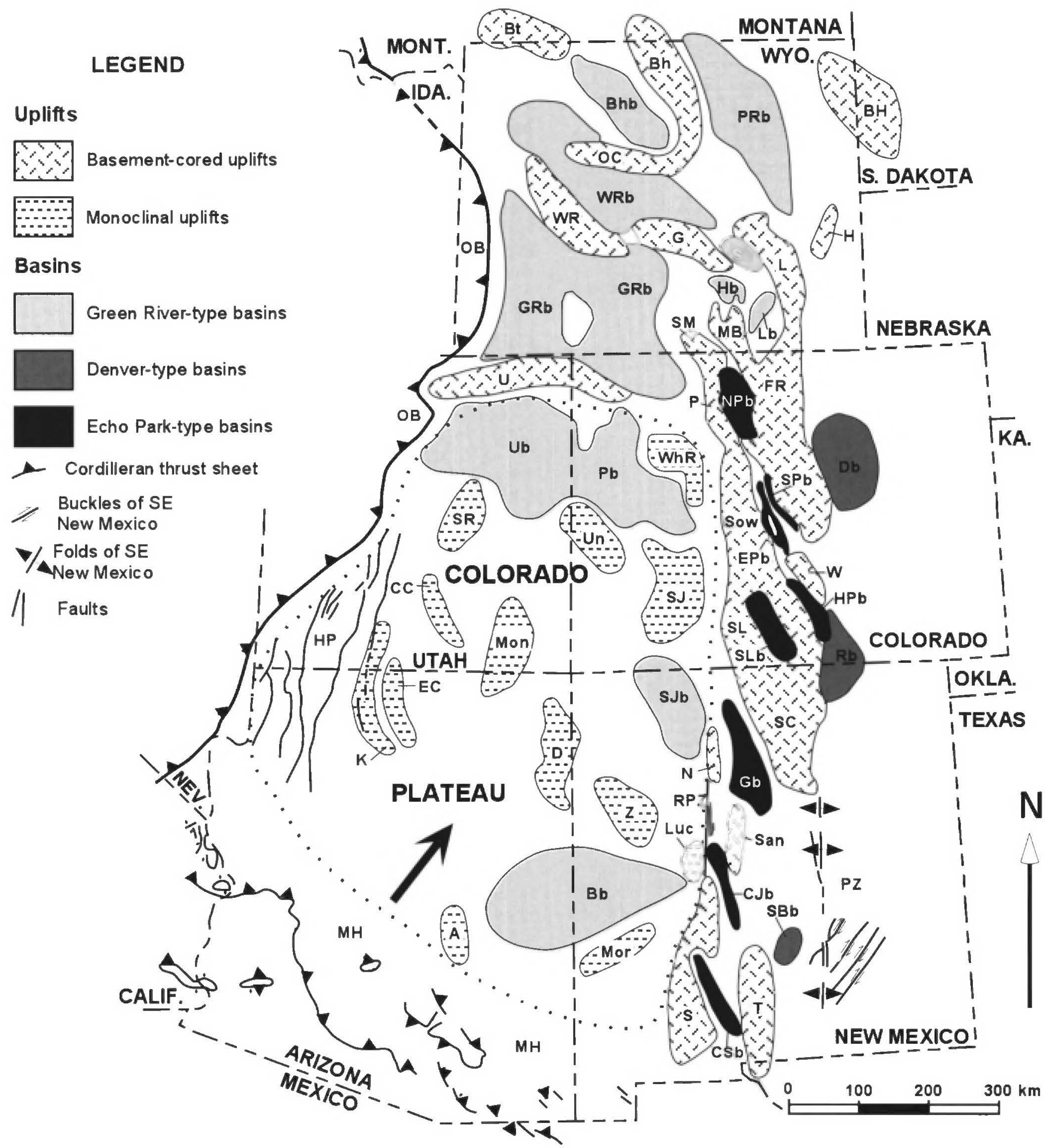

FIGURE 11. Map showing distribution of Laramide uplifts and basins and related structural features in the western U.S. The dotted line indicates the approximate boundary of the Colorado Plateau in the Eocene. The western overthrust belt (OB) and Mogollon highland (MH) are Sevier orogeny highlands west of the main areas affected by the Laramide orogeny. Colorado Plateau monoclinal uplifts are the White River (WhR), San Rafael (SR), Uncompaghre (Un), San Juan (SJ), Circle Cliffs (CC), Monument (Mon), Kaibab (K), Echo Cliffs (EC), Defiance (D), Zuni (Z), Lucero (Luc), Apache (A), and Morenci (Mor) uplifts. Basement-cored uplifts are the Beartooth (Bt), Bighorn (Bh), Black Hills (BH), Owl Creek (OC), Wind River (WR), Granite (G), Laramie (L), Hartville (H), Uinta (U), Sierra Madre (SM), Park (P), Medicine Bow (MB), Front Range (FR), Sawatch (Saw), San Luis (SL), Sangre de Cristo (SC), Wet (W), Nacimiento (N), Sandia (San), Sierra (S), and Tularosa (T) uplifts. Green River type or foreland-like basins are the Bighorn (BhB), Powder River (PRb), Wind River (WRb), greater Green River (GRb), Shirley (Sb), Hanna (Hb), Laramie (Lb), Uinta (Ub), Piceance (Pb), San Juan (SJb), and Baca (Bb) basins. Denver-type basins are the Denver (Db), Raton (Rb), and Sierra Blanca (SBb) basins. Echo Park-type or transtensional basins are the North Park-Middle Park (NPb), South Park (SPb), Echo Park (EPb), Huerfano Park (HPb), San Luis (SJb), Galisteo-El Rito (Gb), Carthage-La Joya (CJb), and Cutter sag-Love Ranch (CSb) basins. Fold and fault zones are the Pecos zone (PZ) and High Plateaus (HP) fault zones (modified from Chapin and Cather, 1981).

the eastern flank of the uplift. Elsewhere, a few north- to northeast-trending minor open folds are present with a few, small high-angle, north- to northwest-trending faults with minor displacement (Kelley and Clinton, 1960).

Nacimiento uplift

The north-trending Nacimiento uplift is about 80 km long and 10–16 km wide (Figs. 1, 11). In general, it consists of an uplifted block that is tilted eastward and is bounded on the west by reverse and thrust faults that cut the right-shifted and folded eastern margin of the San Juan Basin. Structural relief between the highest part of the uplift and the adjacent San Juan Basin is at least 3000 m.

The Nacimiento fault system, bounding the western side of the uplift, has a north strike for about 110 km and consists of four separate, overlapping faults (Woodward et al., 1972; Woodward, 1987; Woodward et al., 1992). Early deformation along the Nacimento uplift is interpreted to have had some component of dextral shift across a zone at least 5-km wide because the Phanerozoic sediments through the Eocene San Jose Formation are folded into northwest-trending en echelon folds (Baltz, 1967; Ruetschilling, 1973). Later, as the Nacimiento block was vertically upthrust, a large west-facing monocline refolded the en echelon folds. Lastly, both the en echelon folds and the monocline were cut by reverse faults as predominantly dip-slip component of the Nacimiento fault system propagated towards the surface. Because the en echelon folds at the northern end of the fault system predate their truncation by reverse fault movement there is differential folding on either side of the fault. As a result their axes cannot be used to determine unequivocally the amount of strike slip movement on the Nacimiento fault segments. The often cited value of ~5 km of right shift during formation of the en echelon folds (Baltz, 1967) is a best-guess estimate of trying to reconstruct piercing lines.

East of the range-margin faults the western margin of the uplift is defined by an anticlinal bend. The northern end of the uplift is a broad, faulted anticline that plunges 10–20° northward. The uplift terminates toward the south with folds that plunge to the south beneath an unconformable cover of Cenozoic rocks (Slack, 1973). Other structures within the uplift include north-striking normal faults that bound second-order, tilted fault-blocks at the northern end of the uplift and a graben in the southern part of the uplift. There are also high-angle faults trending east-west, northwest, and northeast. These faults coincide with segments of the Nacimiento fault system that have differentially uplifted the range.

Sangre de Cristo uplift

The Sangre de Cristo uplift is one of the largest Laramide uplifts of the Rocky Mountain foreland, being nearly 320-km long with an arcuate north trend, and up to 45-km wide (Figs. 1, 8). The western margin of the uplift bounds the Rio Grande rift. Locally, this contact is marked by normal faults, but elsewhere, sedimentary fill of the rift unconformably onlaps the Precambrian basement rocks of the uplifts (Kelley, 1978). It is likely that the western margin of the uplift in Laramide time was west of its present margin, perhaps extending all the way to the Nacimiento front, as rift extension has structurally inverted the older uplift (e.g., Cather, 1992). The eastern margin of the uplift is characterized by reverse faults and a steep monocline characteristic of the Front Range farther north in Colorado (Prucha et al., 1965; Schowalter, 1968; Baltz, 1972; Goodknight, 1973). Based on calculations of depth to Precambrian basement using gravity data for the Rio Grande rift near Española (Cordell, 1976, 1979), probably about 4600 m of structural relief is present on the western side of the uplift. At the southern end, the uplift dies out with gentle, south and southeast-plunging, open, upright anticlines and synclines.

Syn-Laramide sedimentation

During the Eocene (Plates O, R), a syn-Laramide basin in the vicinity of Lamy and the Hagan embayment, called the Galisteo basin (Fig. 11), received up to 1280 m of fluvial strata of the Diamond Tail and Galisteo formations. Sediments were probably in part derived from the adjacent Sangre de Cristo uplift as well as uplifts farther to the west (Stearns, 1943, 1953a; Gorham, 1979; Gorham and Ingersoll, 1979; Cather, 1992; Lucas et al., 1997). These deposits are coeval with the San Jose Formation in the San Juan Basin and indicate that a major east-flowing fluvial system had developed to drain the Laramide uplifts eastward into the Gulf of Mexico (Lucas, 1982; Smith, 1988, 1992). The sediments from that fluvial system are preserved only in flexural downwarps genetically related in an unclear way to the uplifts.

OLIGOCENE VOLCANISM

Sedimentation into the Galisteo and related basins continued through the late Eocene and into the early Oligocene, with provenance changing from detritus shed from Laramide uplifts to sediments and volcanic material derived from volcanic centers. Regionally, the Oligocene was a time of extensive pyroclastic eruptions of ignimbrites (ash-flow tuffs) from caldera complexes in southwestern Colorado (San Juan Mountains) and southwestern New Mexico (Mogollon-Datil field). Preceding and coeval with the "ignimbrite flare-up" were smaller volcanic centers located along the contact between the Laramide Front Range and the High Plains, including Sierra Blanca, the Capitan Mountains, the Ortiz porphyry belt (Fig. 1) of New Mexico, and the Spanish Peaks of Colorado.

The Ortiz porphyry belt is a NNE-trending group of Oligocene stocks, laccoliths, sills, and dikes. Higher structural levels of the intrusions are exposed from south to north (Maynard, 1995). The igneous rocks of the Ortiz Mountains are divided into an earlier calc-alkaline group (34 ± 2.2 Ma) and later alkaline group (30–28 Ma). Gold mineralization is associated with the alkaline rocks (Maynard, 1995). Detritus eroded from the Ortiz Mountains was deposited in the Galisteo basin as a large apron of volcanic detritus called the Espinaso Formation (Stearns, 1953b; Katz et al., 1981; Smith et al., 1991). Deposition was accompanied by the formation of broad, north-plunging, faulted folds (Stearns, 1953a). The original outline of the Galisteo basin is obscure, as it has been modified by younger events including intrusion of the Ortiz and related igneous bodies, development of the Rio Grande rift and related normal faulting, the emergence of the Sandia uplift, and extensive late Cenozoic erosion. However, syn-Laramide deposits thicken to the southeast against the Tijeras-Cañoncito fault zone, suggesting a basin geometry consistent with a transtensional origin (Cather, 1992).

RIO GRANDE RIFT

The geology and landscapes of the Albuquerque area, while reflecting a long history of major global change and tectonism, have been shaped profoundly by the most recent chapter in its geologic evolution—major crustal thinning and extension associated with the Rio Grande rift (Fig. 12). Rifting has played a major role in modifying older structures of Laramide ancestory and subsequent Oligocene volcanism.

Early rift-related deformation

Evidence for crustal extension as early as the Oligocene consists of narrow, but deep basins filled with volcaniclastic sediments. For example, recent drilling has disclosed the presence of thick (as much as 600 m) Oligocene volcaniclastic sediments in linear basins adjacent and parallel to the Rio Grande rift (e.g., Lozinsky, 1994; Hawley, personal comm.). These deposits have no correlatives exposed in immediately adjacent rift flank locations, and it is unclear if they represent deposits proximal to a now buried volcanic source or are the distal equivalent of known volcaniclastic aprons such as the Datil Group. The implication of the former is that there were Oligocene "rift" basins with a similar configuration to the younger, superposed Neogene basins. In northern New Mexico, a debate continues regarding the origin of the Oligocene Abiquiu Formation (Smith, 1996; Moore, unpublished data). Although sourced from volcanism to the north (San Juan field) and east (Latir field), it is unclear if the thick accumulations of the Abiquiu Formation in the Chama embayment reflect early-rift subsidence associated with

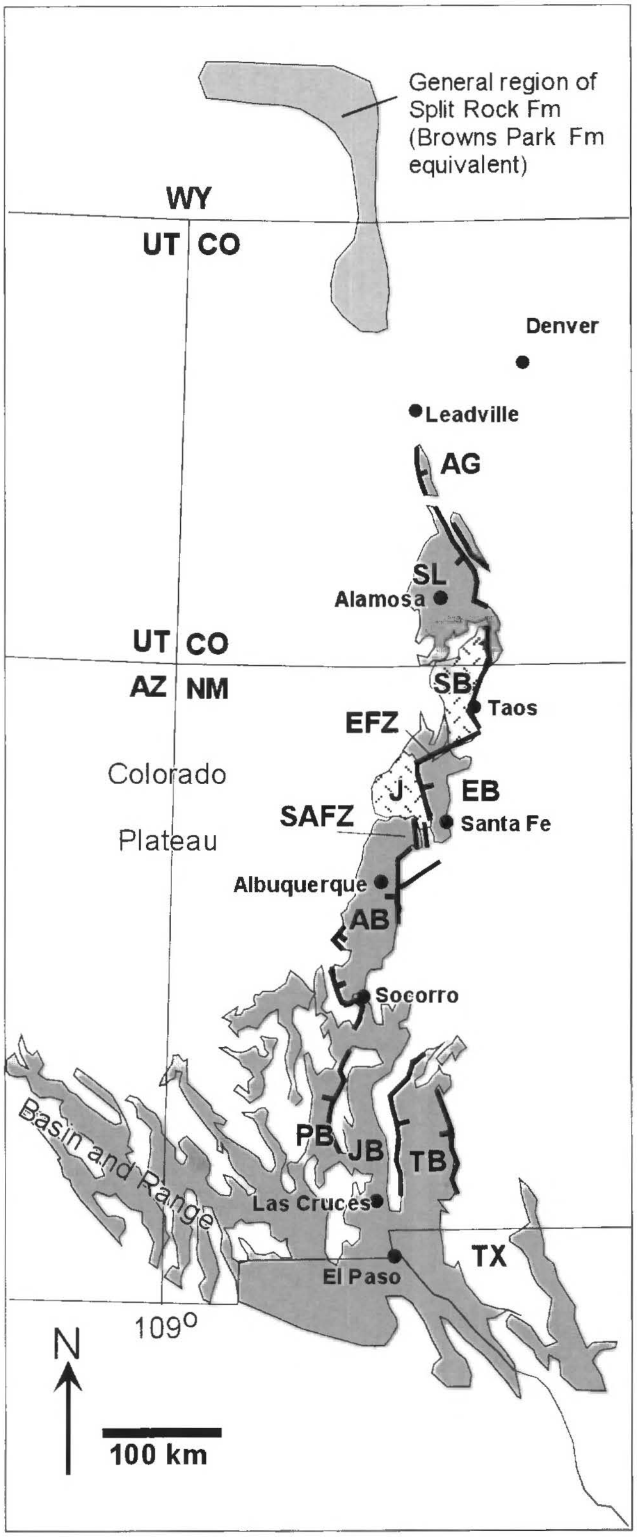

FIGURE 12. Map showing the Rio Grande rift from El Paso to central Wyoming. Major rift basins are the Arkansas graben (AG), San Luis basin (SL), Española basin (EB), Albuquerque basin (AB), Palomas basin (PB), Jornada basin (JB), and Tularosa basin (TB). Important accommodation zones that mark changes in basin subsidence polarity are the Embudo fault zone (EFZ) and the Santa Ana fault zone (SAFZ). Volcanic rocks of the Jemez Mountains (J) and the Sevilleta basalts (SB) in the southern San Luis basin are also shown. Neogene basin fill in northern Colorado and southern Wyoming shows the region north of the Rio Grande rift proper that was also affected by Neogene extension related to the southwest movement of the Colorado Plateau (modified from Baldridge et al., 1984).

high-angle normal faults, a broad, early-rift sag, aggradation driven by overwhelming volcaniclastic sediment supply, or some combination of these processes.

In addition to the evidence for Oligocene extension so closely following Laramide compression, there is mounting evidence of local, transpression and dextral strike-slip faulting (Erslev, this volume). Broad folds in Oligocene–early Miocene rocks of north-central Colorado, traditionally attributed to rift-related normal faults (Chapin and Cather, 1994), and dextrally offset Oligocene dikes in the Hagan embayment and in northeastern New Mexico are field observations that have been reinterpreted to support the concept of post-Laramide compressional tectonics. It is instructive to note that evidence for both extensional and compressional deformation during the Oligocene can be reconciled in a strike-slip model along which both transtensional and transpressional conditions are accommodated.

A further complication to the picture of Oligocene tectonism concerns the exact timing of the uplift of Sierra Nacimiento and Sierra Lucero, two ranges that are traditionally regarded as Laramide in origin (see above). However, several workers have noted that these uplifts may be significantly younger, with the implication that Laramide-style deformation continued longer in New Mexico than elsewhere in the Rocky Mountains (Slack and Campbell, 1976; Kelley, 1977). The Pedernal Chert, which rests unconformably on top of Precambrian rocks at San Pedro Parks in the northern Sierra Nacimiento (Fig. 1), offers an example of this late-stage Laramide-style deformation. The ~26-Ma Pedernal Chert is a member of the Abiquiu Formation that is present only in exposures outside of the rift (i.e., on the Colorado Plateau). At the type section on Cerro Pedernal, the Pedernal Chert lies at ~2400-m elevation. At San Pedro Parks, the Pedernal Chert lies at ~3200-m elevation. Farther west in the San Juan Basin on the continental divide at Haynes Flat, abundant float of Pedernal Chert attests to a likely former extent at ~2400-m elevation (Formento-Trigilio and Pazzaglia, 1998), or very similar to its elevation at Cerro Pedernal. There are several syn-rift faults between Cerro Pedernal and San Pedro Park to account for the 800-m discrepancy in elevation. The only structure between San Pedro Parks and Haynes Flat is the Nacimiento fault system, which implies as much as 800 m of post-26 Ma movement on a thrust fault of supposed Laramide age. Rift-flank uplift, and flexural deformation of the footwall might have been able to produce a similar deformation of the Pedernal Chert stratigraphic horizon (Roy et al., this volume); but these geodynamic processes remain to be demonstrated.

Several important late Oligocene events lead to the development of the Rio Grande rift and coeval sculpting of the Colorado Plateau and High Plains. During the late Oligocene major core complexes began forming south and west of the Colorado Plateau. The high-standing topographic welt that had been constructed during the Sevier and Laramide orogenies was collapsing (Sonder et al., 1987), marking the onset of crustal extension and development of the Basin and Range. This crustal extension caused the Colorado Plateau to reverse its sense of relative motion during the Laramide orogeny and begin to translate west and south. As the Colorado Plateau pulled away from the craton, the high-standing Laramide welt began to collapse (Chapin and Cather, 1994). The Laramide topography was progressively structurally inverted, and by the beginning of the Miocene (23 Ma; Plate P), structural lows began accommodating eolian and fluvial sediment. A narrow zone of extended lithosphere developed from central New Mexico northward through Colorado and into southern Wyoming.

At about the time that Basin and Range extension was initiated, a broad region stretching from the Colorado Plateau to the High Plains began to undergo dissection by fluvial erosion. Evidence for this erosion is displayed by the exhumation of the Ortiz and related intrusions such as the Spanish Peaks, which formerly penetrated a thick Cretaceous-through-Oligocene sedimentary cover. Locally preserved Oligocene rocks, including the Abiquiu Formation beneath Cerro Pedernal, suggest that the stripping began in the late Oligocene–early Miocene. Initially, most of the rocks removed by the fluvial erosion were soft Mesozoic and Cenozoic sedimentary rocks. By the middle to late Miocene, significant amounts of hard crystalline rocks were exposed in the Front Range. These rock types are more conducive to the production of coarse grain sizes and, together with the progressive general cooling and increased physical weathering of late Cenozoic climate, resulted in coarser bedloads for the streams exhuming the Rocky Mountains. This passage of such coarse bedload through fluvial systems is recorded as a complex array of valley fills and terraces collectively called the Ogallala Formation. Fluvial exhumation of the southern Rockies continues to the present. Its cause could be linked to steepening of fluvial gradients as the entire Rockies were epeirogenically uplifted and tilted by buoyant mantle (the Alvarado ridge of Eaton, 1986).

Structural setting

Structural development of the Albuquerque basin was more or less typical of all rift basins in the Rio Grande rift. The Albuquerque basin initiated as broad, relatively shallow structure (Chapin and Cather, 1994). As extension continued, the basin deepened and became narrower. To a first order, the basins are asymmetric grabens. Subsidence polarity changes longitudinally across complex accommodation zones between major basins and occasionally within a basin. For example, in northern New Mexico, the Albuquerque and San Luis basins are down to the east, but the intervening Española basin is down to the west. Locally, the flanks of the Rio Grande rift are elevated and bowed outward away from the deep side of the basin. Such rift flank uplifts are thought to be associated with major extensional faults which have unloaded a footwall block, allowing it to rise isostatically (May et al., 1994; Roy et al., this volume). Thus, the total elevation of some ranges in the rift may have their origins due to unequal contributions of Laramide crustal shortening in the late Cretaceous–Eocene, epeirogenic uplift associated with the mantle-driven development of Alvarado ridge in the late Oligocene, and flexural isostatic uplift of the rift flanks associated with crustal thinning from the Miocene to present (Roy et al., this volume).

Rift stratigraphy

The Rio Grande rift is filled with a complex suite of axial stream, floodplain, lacustrine, eolian, piedmont, and tributary stream facies collectively called the Santa Fe Group (Bryan and McCann, 1937; Bryan, 1938). Detailed description and discussion of these deposits can be found in the Second-day Road Log, and in papers by Connell et al. and by Tedford and Barghoorn in this volume. Our descriptions here are summarized from these sources. The oldest rift sediments in the Santa Fe Group belong to the early–middle Miocene Zia Formation and are preserved in the footwall shoulder in the Rio Puerco fault zone along the western margin of the rift. Sediments of similar age, if they ever existed, are not exposed along the eastern margin of the Albuquerque basin, which attests to its down-to-the-east basin asymmetry. Only in the rift shoulder of the Hagan basin are there deposits of similar age to the Zia Formation (Stearns, 1953a; Kelley, 1977). It is a general observation that the rift fill, which begins as mostly eolian sand of the Zia Formation, makes a transition to predominantly coarser fluvial facies upsection. The middle–late Miocene and Pliocene–Quaternary parts of the Santa Fe Group record an increasing input of reworked Abiquiu Formation and Jemez volcanic rocks. Most of the sediment that filled the Albuquerque basin was derived from the north and transported there by a few large river systems, including the paleo-Rio Grande and paleo-Rio Puerco.

LATE CENOZOIC LANDSCAPE EVOLUTION

Major landforms

The major landforms in the Albuquerque area (Fig. 2) facilitate reconstructing the climatic and tectonic history of the middle Rio Grande basin through the Neogene and Quaternary. The region is dominated by the south-flowing Rio Grande and the wide valley it excavated in the past 1 m.y. The Rio Grande became a through-going axial drainage in the Albuquerque basin ~5 Ma, at the beginning of Sierra Ladrones Formation deposition (Lozinsky, 1994). Prior to that time, the river terminated in the basin and, along with the Rio Puerco, fed a large fan-delta. West of the Rio Grande is a broad, low-relief surface called the Llano de Albuquerque that stretches west for 20 km to the Rio Puerco valley. The west-facing escarpment of the Llano is called the Ricones del Rio Puerco and its northern terminus at the Jemez River valley is called La Ceja (the "eyebrow" in Spanish). To the south, the Llano de Albuquerque tapers to a point as the Rio Puerco nears its confluence with the Rio Grande. Two Quaternary volcanic fields sit atop the Llano de Albuquerque, the Cat Hills to the south and the Albuquerque volcanoes to the north. Although appearing smooth from a distance, the surface of the Llano de Albuquerque has a fair amount of corrugated topography formed by faults, fluvial dissection, and constructional eolian deposits. An important distinguishing characteristic of the Llano de Albuquerque is a well-developed, polygenetic calcic soil.

Several related extensive geomorphic surfaces are present in the Albuquerque area. East of the Rio Grande are the Llano de Sandia and the Llano de Manzano, which form the piedmonts of the Sandia and Manzano Mountains, respectively. The Albuquerque airport is built atop the airport surface, and basalts of the Santa Felipe volcano have preserved an old pediment bottom now expressed as Santa Ana Mesa. The origin and age of these low-relief landforms are discussed below.

The high-standing topography along the eastern rift flank dominates the Albuquerque area. The Sandia Mountains rise 3240 m and extend southward as the Manzanita, Manzano, and Los Pinos Mountains. Tijeras Canyon marks an abrupt southern terminus of the Sandia Mountains that coincides with the northeast-striking Tijeras-Cañoncito fault zone. To the north, the Sandia Mountains terminate more gently, as an almost complete section of upper Paleozoic through middle Cenozoic strata is preserved in a large homocline dipping northeast off of the Sandia block.

Sedimentologic and base level changes in the Albuquerque basin

The Albuquerque basin continued to fill with syn-rift, predominantly coarse-grained fluvial sediments through the Pliocene and into the early Pleistocene. As rifting narrowed in the Albuquerque basin through the late Miocene and into the Pliocene, older rift sediments were uplifted and exposed on the rift flanks. Streams, particularly western tributaries of the Rio Grande, incised into the uplifted footwalls and recycled older Santa Fe Group sediments into a more narrow zone of subsidence localized in the eastern third of the basin. The effect was to produce an incised landscape in the western two-thirds of the Albuquerque basin, where inset fluvial terraces converged downstream (to the east) to eventually become conformable with continued accumulation of Rio Grande axial stream deposits. For example, the Sierra Ladrones Formation, the late Miocene–early Pleistocene, coarse-grained axial stream facies of the Santa Fe Group, is rarely more than 100-m thick west of Rio Rancho. However, east of Rio Rancho, under Albuquerque, and stretching to within a few kilometers of the Sandia Mountains, the Sierra Ladrones Formation is hundreds of meters thick (Connell et al., 1997; Hawley, unpublished data). Viewed in this way, it is clear that any geomorphic surface underlain by Santa Fe Group strata must be diachronous. Many of the broad, flat geomorphic surfaces common to the Albuquerque basin, such as the Llano de Albuquerque, do not represent a single constructional (depositional) top of the Santa Fe Group, everywhere abandoned more or less isochronously. Rather, such surfaces are complex and polygenetic, owing their origin to a long history of recycled Santa Fe Group sediments, diachronous abandonment in the face of continued footwall uplift and basin-floor tilting, and later local modifications attributed to fluvial and eolian processes.

In contrast, eastern tributaries to the Rio Grande, particularly those draining regions like the Hagan basin that were not greatly affected by rift-flank processes, did not incise into uplifting footwalls. These tributaries experienced protracted periods of base level stability or rise, which favored lateral instead of vertical fluvial incision and the formation of broad pediments. Extensive extrusion of basalts throughout the

Albuquerque basin in the middle–late Pliocene has fortuitously preserved some of these low-relief pediments. As erosion has progressed, the topography has been inverted. Former middle Pliocene valley bottoms filled by the basalt stand high as mesas whereas the former divides, not covered by basalt, have been removed and reduced to low-standing topography. The Hagan basin is unique in that it preserves the best example of a widespread middle Pliocene pediment not associated with a basalt flow. Tilted Mesozoic–early Cenozoic strata in the Hagan basin are beveled (the pediment), and are overlain by several meters to tens of meters of coarse sand and gravel called the Tuerto Formation (Stearns, 1953a). In one locality near La Bajada, the Tuerto Formation is overlain by a basalt flow dated at ~2.6 Ma (Bachman and Mehnert, 1978), which indicates a middle–late Pliocene age for its deposition, and an older, unknown age for the cutting of the pediment at its base.

One of the more intriguing observations of Albuquerque area geomorphology is that the ~500 m of relief in the Rio Grande valley is the result of fluvial incision, rather than tectonic subsidence associated with the rift. Deposition of the Santa Fe Group continued more or less unabated through the early Pleistocene in actively subsiding parts of the basin. Presence of the lower and upper Bandelier pumices near the top of the Santa Fe Group attests to rift-related basin aggradation as recently as 1.2 Ma. Since that time, the Rio Grande has incised, carving out a wide valley through its former deposits. Even if basin subsidence has slowed throughout the Quaternary, it has not ceased, as there is still microseismicity (Sanford et al., 1991) and numerous examples of fault rupture of Quaternary deposits (Personius et al., this volume; Connell and Wells, this volume). Thus, it is unlikely that there is a local tectonic reason for the fluvial excavation of the Rio Grande valley. We explore the possibility that basin-wide changes in hydrology and sediment yield related to climate change could be driving the incision.

Fluvial entrenchment of the Rio Grande is not restricted to the Albuquerque basin. It is a geomorphic response observed throughout the rift from near the Colorado-New Mexico border to Las Cruces (e.g., Hawley, 1978). The rate of incision has been remarkably uniform (spatially) from the Española valley to the Mesilla valley, but it has not been steady (temporally). Long-term fluvial incision has been punctuated by several episodes of valley bottom widening and aggradation of ~10–30 m of coarse-grained deposits with a predominantly northern provenance. Subsequent incision following one of these aggradation pulses has resulted in the preservation of coarse-grained deposits as a fluvial terrace.

At least three major Pleistocene terraces are preserved in the Albuquerque basin. In order of elevation above the Rio Grande floodplain they are called Primero Alto (~20 m above the floodplain), Segundo Alto (~40 m above the floodplain), and Tercero Alto (>50 m above the floodplain) (Bryan and McCann, 1938; Lambert, 1968). Segundo Alto is better known as the Edith gravel (Lambert, 1968). A fourth coarse-grained deposit lies buried beneath the modern Rio Grande floodplain. A likely origin for these coarse Pleistocene alluvial fills is glacial-interglacial-scale climate changes that have changed the discharge and sediment yield of the Rio Grande. A recent age estimate of the Albuquerque volcano basalts at 156 ± 29 ka (Peate et al., 1996) supports this climatic origin of the terraces. A fine-grained facies of the Edith gravel called the Los Duranes Formation (Lambert, 1968) interfingers with a flow from the Albuquerque volcanoes. Thus, the Edith gravel is also ~156 ka, and was deposited during a well-known glacial outwash event in the Rocky Mountains at the end of marine oxygen isotope stage 6 (Illinoian or Bull Lake time). Following from the age of the Edith gravel, the ~30 m of coarse alluvium beneath the Holocene Rio Grande floodplain is thought to represent glacio-fluvial outwash associated with late Pleistocene glaciation during marine isotope stage 2 (late Wisconsinan or Pinedale) ~20 ka. Although the origin of the Pleistocene terraces may be understood in terms of climate change, one would expect the same climate changes to significantly modify the transport gradient of the Rio Grande as it alternately carried gravel (glacial outwash) and sand (modern stream). However, no significant change in terrace-to-floodplain gradient is observed over hundreds of kilometers of river valley between Cochiti Lake and Las Cruces (Hawley, 1978).

Middle and late Pleistocene climates, such as glacial-interglacial cycles and highly seasonal rainfall, represent the most likely explanation of the widespread entrenchment of the Rio Grande in a still subsiding rift. However, there are other documented events that may have exacerbated the incision. In the San Luis basin of northern New Mexico, the Rio Grande is incised through a narrow, 200-m-deep gorge in the Sevilleta basalts. That gorge ends as a broad knickzone north of the Red River confluence with the Rio Grande. North of the knickzone, lacustrine basin-fill facies with interbedded Lava Creek B ash are preserved (Rogers, 1985), indicating that this part of the San Luis basin was internally drained as recently as 620 ka. Integration of the Rio Grande headwaters north of the Red River confluence after 600 ka, effectively adding all of the Colorado-San Juan Mountains part of the drainage, would have dramatically increased discharge for the Rio Grande downstream of the San Luis basin and promoted incision (Wells et al., 1987). It is clear however that Rio Grande incision had begun prior to ~600 ka, as the Lava Creek B ash is preserved in inset terraces in the Española valley (Dethier et al., 1988) and elsewhere.

Sandia Mountains

Late Cenozoic landforms and deposits in the Sandia Mountains reflect a complex interaction of tectonic and climatic processes. The imposing west-facing Sandia escarpment is clearly a product of faulting. Numerous facets, particularly well preserved along Rincon Ridge and in the La Cueva Canyon area (Kelley and Northrop, 1975) attest to normal faults at the mountain front-piedmont boundary. Locally, Pleistocene alluvial fan deposits are ruptured (Connell, 1995; Connell and Wells, this volume), which indicates that the range-bounding faults remain tectonically active. Several lines of evidence suggest that uplift of the Sandia Mountains occurred in two phases: (1) facets are present only in the lower third of the mountain front or on Rincon Ridge, (2) faceted spurs are accordant with the top of Rincon Ridge, (3) drainage hypsometry is consistent with a recent base-level fall (Gustafson, 1996), and (4) there is an extensive pediment buried beneath thin alluvial fan deposits west of the mountain front.

These observations could be explained with a phase of uplift during early rift extension, or possibly even during Laramide deformation (Karlstrom et al., this volume), followed by tectonic quiescence and eastward retreat of the mountain front escarpment. Only one generation of facets coincident with the lower third of the Sandia mountain front suggests that Rincon Ridge was not yet present during this phase of deformation. During later stages of rift extension, a second phase of uplift utilizing the same faults, as well as new ones, created Rincon Ridge and rejuvenated the Sandia mountain front. This later stage of uplift might be coincident with down-to-the-east basin tilting in the late Miocene and Pliocene, which drew the ancestral Rio Grande east, depositing Sierra Ladrones Formation strata beneath the northeast heights of Albuquerque. West-flowing mountain front streams incised through the pediment produced during the preceding escarpment retreat and formed the concordant faceted spurs and deep, V-shaped canyons between facets. Subsequent tectonic quiescence and associated base level stability again favored eastward retreat of the west-facing escarpment and the formation of a pediment stretching westward from the mountain front.

Although broadly consistent with the mountain front landforms, this reconstruction of uplift and escarpment retreat events is not well supported by geophysical evidence for the location of the large, range-bounding structures. For example, Bouguer and isostatic gravity data for the Albuquerque basin (Plates C, D) clearly show that the depth to bedrock is very shallow for most of the Sandia piedmont west to at least the present location of Juan Tabo Blvd. These observations are corroborated by both mapping (Lambert, 1968; Connell, 1995; Gustafson, 1996), and by water-well data (Connell et al., 1997). If the large, down-to-the-west normal faults suggested by these data lie several kilometers west of the mountain front, either a significant amount of eastward escarpment retreat has occurred, or the interpretation of mountain front landforms must be reconsidered. A poor coincidence between geophysically- and geomorphically-defined mountain front-basin boundaries exists for many parts of the Basin and Range province.

The Sandia piedmont, although in part related to the tectonic events that uplifted the Sandia Mountains, also in part owes its origin to late Cenozoic climatic changes. The piedmont is underlain by several inset middle Pleistocene–Holocene alluvial fans that bury a broad, pre-middle Pleistocene pediment of low relief (Connell, 1995; Gustafson, 1996). The alluvial fan deposits exhibit well-stratified, fluvial sand and gravel bases that coarsen upward to car-size corestones deposited by debris-flow processes. Granule and sand-fraction material is almost exclusively grus sourced from the chemical and mechanical weathering of the Sandia Granite.

Weathering and related hillslope processes on the Sandia mountain front are likely linked to the observed alluvial fan stratigraphy and buried pediment. We propose that prior to the middle Pleistocene, a time significant in that it predates the onset of large amplitude glacial-interglacial climate cycles, granitic hillslopes in the Sandia Mountains were subject to a greater degree of chemical and mechanical weathering than at present. These hillslopes had a significant regolith cover, were transport-limited, and supported perennial streams draining the escarpment. Under these conditions, hillslopes underwent extensive corestone weathering, but most of that weathered material remained on the hillslopes. Perennial streams with a constant base level swept out a low-relief pediment west of the escarpment. With the onset of 100-ka glacial interglacial cycles at ~800 ka, the hydrology and processes operating on the Sandia hillslopes changed. Glacial-interglacial climate cycles favored hillslopes becoming increasingly more weathering limited as regolith was stripped. With less regolith, runoff became dominated by overland flow. With less subsurface flow necessary to regulate stream base flows, escarpment drainages became more ephemeral. Pedimentation ceased, and the material transported off the hillslopes in the past 800 ka has accumulated as alluvial fan deposits, burying the pediment. As the roots of the former pre-middle Pleistocene weathering profile become progressively exhumed, corestones litter the modern Sandia hillslopes and explain why alluvial fan deposits coarsen upwards. In essence, the fan stratigraphy reflects an "unroofing" during the past 800 ka of a pre-middle Pleistocene weathering profile.

CONCLUDING REMARKS

One of the more remarkable features of the geology in the Albuquerque area is the diversity of processes that have interacted to produce the rocks and landforms we will inspect during the Field Conference. A full understanding of these interactions will be the pursuit of geologists for many years into the future, especially in the context of how a growing population in the middle Rio Grande basin places expanding pressures on local resources. We have acquired much new data in the past 17 years since the last Albuquerque country conference which has allowed us to: (1) better appreciate of the role of ancient basement structures in the tectonic evolution of New Mexico, (2) better integrate geologic and geophysical data in our understanding of the Rio Grande rift, (3) propose some insights into the role of the upper mantle in driving volcanism and epeirogenic uplift, (4) develop a fuller understanding of the Phanerozoic stratigraphy in the context of global change, and (5) redefine rift stratigraphy in the context of our water resources.

Our summary of the geologic history of the Albuquerque area illuminates several strongly debated issues that are discussed in this volume. These include: (1) the degree and timing of dextral offset across and along the Rio Grande rift (Woodward et al., this volume); (2) a re-evaluation of the origin of uplifts such as the Sandia Mountains, coincident with the rift flank (Roy et al., this volume); (3) the origin of the rift and rift stratigraphy in the context of the regional high-standing topography (Connell et al., this volume; Tedford and Barghoorn, this volume; Karlstrom et al., this volume); and (4) the active tectonic setting of the rift (Personius et al., this volume; Connell and Wells, this volume). Hopefully, the long-standing commitment to field geologic investigations in this state, well supported by the ever increasing abilities of analytical facilities, will foster challenging geologic research to solve these and additional problems in the Albuquerque area for many years to come.

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"While still I may, I write for you
The love I lived, the dream I knew."

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