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SUGGESTED REVISIONS TO THE TERTIARY TECTONIC HISTORY OF NORTH-CENTRAL NEW MEXICO

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Abstract—Based on a variety of new or re-evaluated geological and geophysical constraints, the following modifications to the Tertiary tectonic history of north-central New Mexico are proposed: (1) reverse faulting along the Pajarito fault zone defined the western boundary of a late Laramide basement uplift (Pajarito uplift) that was contiguous with the Sangre de Cristo uplift to the east; (2) the Tijeras fault zone constituted a releasing bend in the right-lateral strike-slip system of the Laramide southern Rocky Mountains and controlled extensional subsidence within an Eocene half-graben to the northwest (the Galisteo basin); (3) development of a flexural hinge along a Laramide precursor to the Santa Ana accommodation zone (new name) may have facilitated the southeastward tilting of the floor of the Galisteo basin and locally delineated the southern boundary of the Pajarito uplift; and (4) the Pajarito uplift began to collapse due to extension beginning in the late Oligocene–early Miocene, and continued subsidence and westward tilting of the resulting Española half-graben caused deposition of about 3 km of Santa Fe Group sediments near the Pajarito fault zone.

INTRODUCTION

The Tertiary geologic history of north-central New Mexico has been relatively well studied, and consists of a Laramide orogenic phase (Late Cretaceous to Eocene) followed by major volcanism and rifting beginning in the Oligocene and Miocene, respectively. The Rio Grande rift lies athwart the late Laramide Galisteo–El Rito basin near Albuquerque. Because of the effects of synrift sedimentation and volcanism, many aspects of the tectonic development of the Galisteo–El Rito basin are obscure.

The Rio Grande rift in north-central New Mexico consists of a longitudinal array of four structural domains that are characterized by opposing stratal-tilt directions relative to adjoining areas (Fig. 1). Several of the basin blocks within these domains have experienced tectonic inversion resulting from collapse of Laramide up-thrust blocks during extension (e.g., Sales, 1983; Cather, 1989, 1990; Brister, 1990). Structural zones that divide domains of opposing dip within the rift are termed accommodation zones (also transverse shear zones or transfer zones; cf. Chapin et al., 1978; Chapin, 1988). These poorly understood structural zones trend northeast (Fig. 1); at least two of the accommodation zones within the rift show evidence of reactivation along pre-rift structures (Socorro accommodation zone, Chapin et al., 1978; Chapin, 1989; Tijeras accommodation zone, Lozinsky, 1988).

This report deals primarily with aspects of the Laramide orogeny in north-central New Mexico, although some topics of Neogene extensional deformation and rift-basin stratigraphy are also discussed. Specifically, I describe structural and stratigraphic data and previously published fission-track cooling ages that bear on the structural development of the Laramide Galisteo basin, and propose that Laramide precursors to the Tijeras zone, the Pajarito fault zone, and the Santa Ana accommodation zone (new name) formed local boundaries of the Galisteo basin. I will focus upon the northeastern basin boundary adjacent to the Brazos–Sangre de Cristo uplift and the southeastern boundary of the Galisteo basin.

NORTHEAST BOUNDARY OF GALISTEO BASIN

Galisteo outcrops near St. Peter's Dome

Heretofore unstudied exposures of sandstone and conglomerate of the Eocene Galisteo Formation crop out near St. Peter's Dome, along the western margin of the Española Basin (Fig. 2). Previous work near St. Peter's Dome consisted mostly of geologic mapping and volcanologic studies of late Cenozoic domes, flows and ignimbrites that dominate the exposures in the area. Smith et al. (1970) were the first to recognize the Galisteo exposures near St. Peter's Dome; previous workers had regarded these exposures as Santa Fe Formation (Dane and Bachman, 1957; Northrop and Hill, 1961) or simply as Tertiary sediments (Ross et al., 1961). Goff et al. (1990) produced an excellent geologic map of the St. Peter's Dome area, but they did not study the Galisteo outcrops in detail.

The Galisteo exposures near St. Peter's Dome occupy an area of approximately 2 km^2 in the footwall of the Pajarito fault zone (Fig. 2). There, the Galisteo is a red-bed sequence with an exposed thickness of about 630 m. The base of the unit is not exposed and the top is unconformably overlain by about 100 m of the Santa Fe Group. The Galisteo is entirely nonvolcaniclastic and dips 25°–45° west, in contrast to the overlying Santa Fe, which dips about 5°–10° to the northwest. The Santa Fe Group at St. Peter's Dome is largely arkosic but contains significant volcanic and volcaniclastic materials (F. Goff, personal comm. 1992), including a 16.5 Ma basalt flow (Gardner and Goff, 1984; Goff et al., 1990).

No fossils have been collected from Galisteo exposures near St. Peter's Dome; assignment to the Galisteo Formation is based on stratigraphic position and similarities in lithology and color to other Eocene deposits in north-central New Mexico. The term "Galisteo Formation" is preferable to "El Rito Formation" for the exposures in the study area due to precedence of use (Smith et al., 1970; Kelley, 1978; Goff et al., 1990) and because the exposure in question is slightly closer geographically to known outcrops of Galisteo Formation to the south than to El Rito exposures to the northwest. This discussion of terminology is somewhat moot, however, as it appears that the two formations were both deposited within a contiguous depositional basin (Spiegel, 1961; Baltz, 1978; Logsdon, 1981; Chapin and Cather, 1981; Lucas, 1984).

I have divided the Galisteo deposits near St. Peter's Dome into three informal members (Fig. 2). These are, in order of ascending stratigraphic position, the lower red sandstone unit, middle pebbly sandstone unit and upper conglomerate unit.

Lower red sandstone unit

This unit is principally composed of fine- to coarse-grained sandstone with subordinate mudstone; conglomerate is rare except for intraformational clay clasts. Sandstone occurs mostly as broad, sheet-like deposits that fine upward and range from about 1 m to 5 m in thickness. Trough crossbedding is typically present in the basal part of individual sandstone beds, and gives way to horizontal stratification upsection. The substantial thickness and lateral continuity of these fluvial sandstones are indicative of deposition by major, sand-dominated rivers. Red coloration predominates throughout the unit in the area.

The lower red sandstone unit has an exposed thickness of about 330 m. Upsection, it grades into and intertongues with the middle pebbly sandstone unit. The base of the lower red unit is in fault contact with the Bandelier Tuff (Fig. 2).

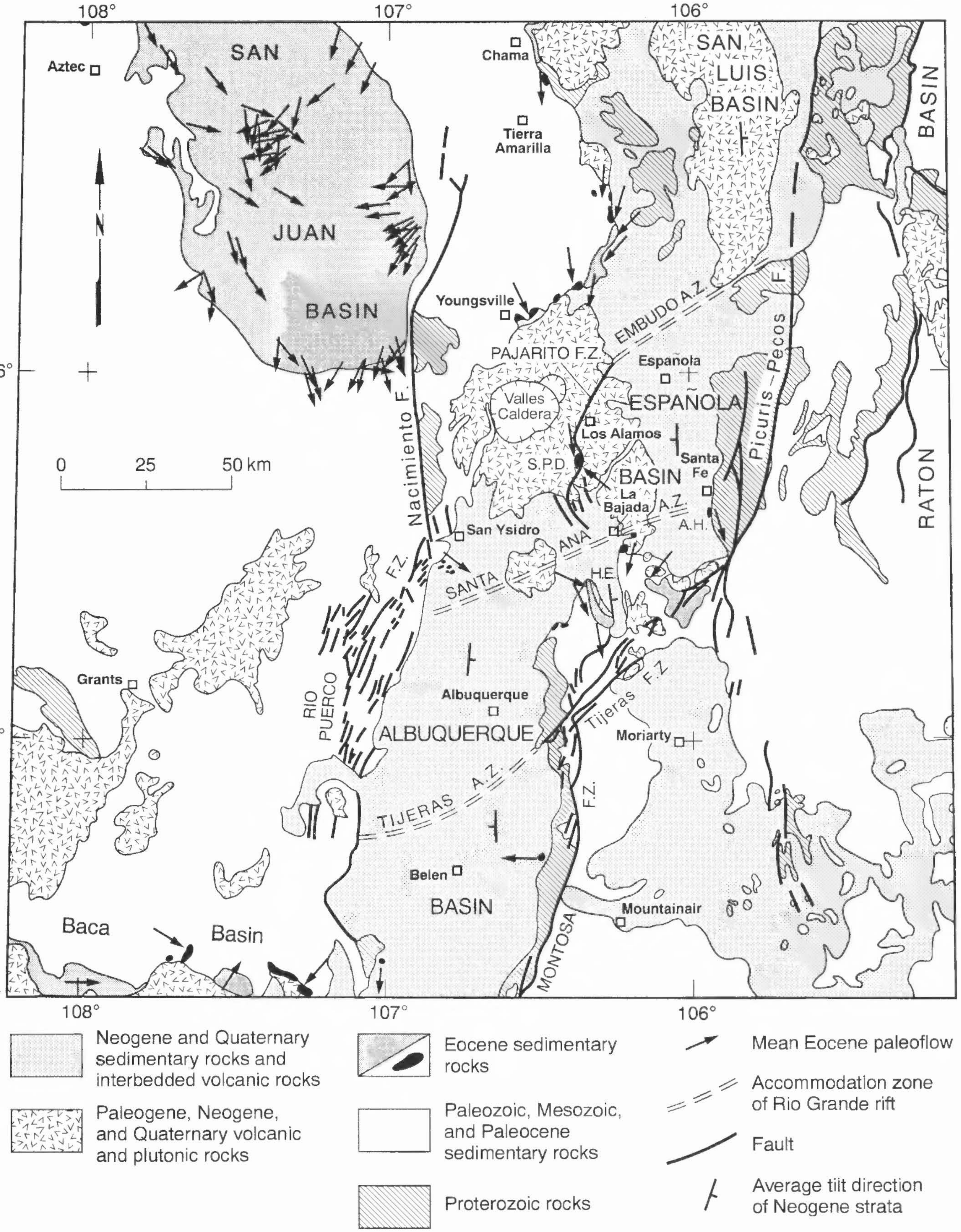

FIGURE 1. Simplified geologic map of north-central New Mexico showing selected structural features and mean Eocene paleoflow vectors (Smith, 1988; Brister, 1990; Logsdon, 1981; Gorham and Ingersoll, 1979; Cather and Johnson, 1984, 1986). Exposures at St. Peter's Dome (S.P.D.) and Arroyo Hondo (A.H.) are discussed in text. Accommodation zones of Rio Grande rift are modified from Chapin (1988). Base map modified from New Mexico Geological Society (1982).

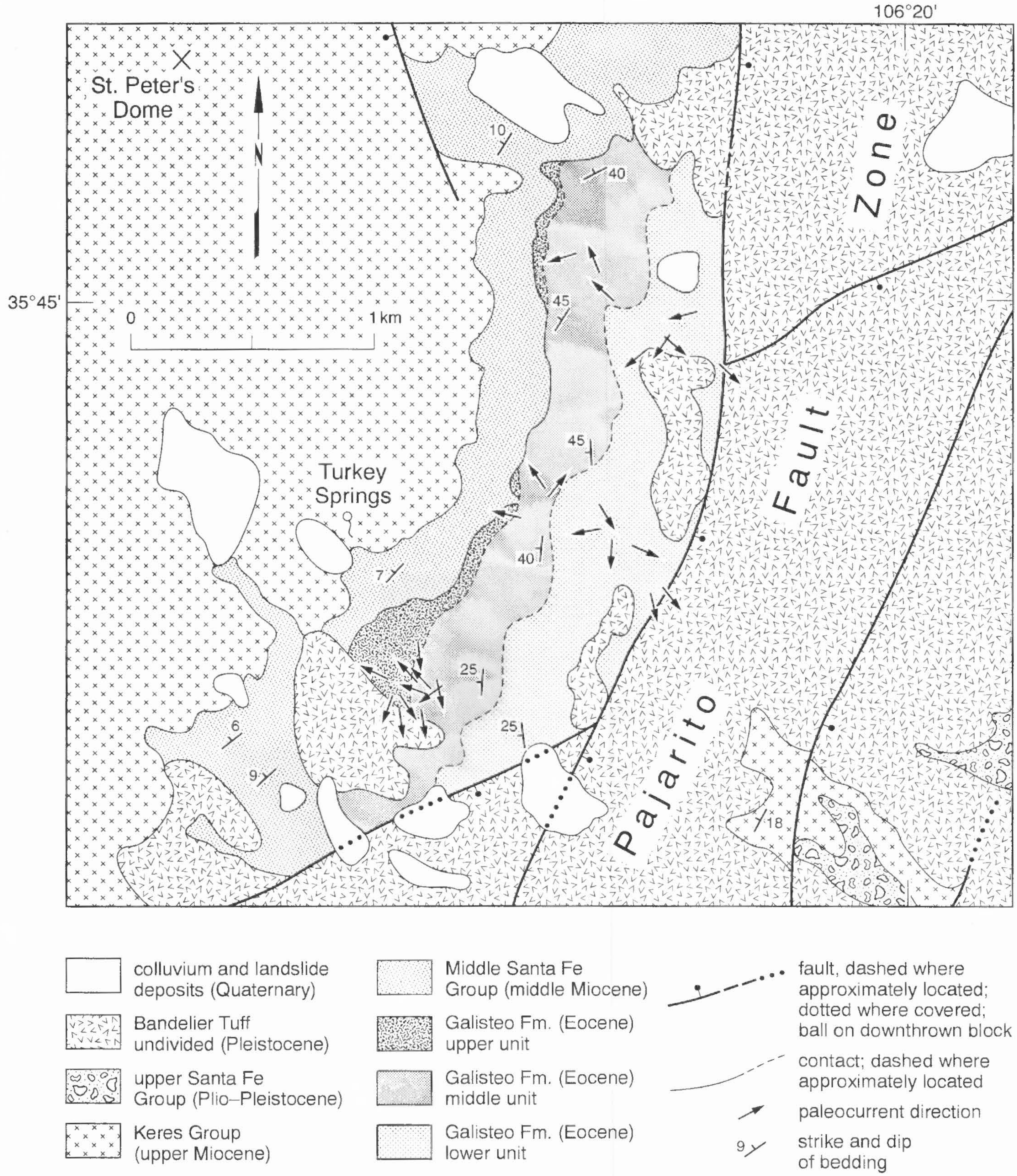

FIGURE 2. Simplified geologic map of St. Peter's Dome area (modified from Goff et al., 1990) showing measured paleocurrent vectors and informal members within Galisteo Formation.

Paleocurrent indicators from the lower red unit (Fig. 3) suggest southerly paleoflow, subparallel to the trace of the Pajarito fault zone. Sandstone thin sections from the unit show subequal amounts of recycled sedimentary detritus (well-rounded monocrystalline quartz and chert grains with subordinate limestone fragments) and basement-derived detritus (angular to subangular polycrystalline grains of metaquartzite, granite-gneiss fragments and feldspar). Taken together, evidence for mixed source terranes and major, south-flowing fluvial systems suggests that the lower red sandstone unit in the study area may represent the deposits of an axial river system in the Galisteo–El Rito basin. In contrast, only remnants of piedmont systems are preserved in the El Rito exposures to the north, and these piedmont systems are locally dominated either by Precambrian detritus derived from the Brazos uplift or by recycled sedimentary detritus eroded from the Gallina-Archuleta arch (Logsdon, 1981).

Middle pebbly sandstone unit

This unit consists predominantly of sandstone but contains significant conglomerate and pebbly sandstone, particularly near the base. Overall conglomerate/sandstone/mudstone ratio is about 20/80/0. The unit is gray to buff in color, and commonly forms steep slopes and cliffs. The middle pebbly sandstone unit is about 150 m thick, and appears to be in transitional contact with the overlying upper conglomerate unit. This contact, however, is poorly exposed.

Bedding in the middle pebbly sandstone unit ranges from about 0.5 to 2 m thick; horizontal stratification, trough crossbedding and planar foreset bedding are the dominant sedimentary structures. Maximum clast size is about 8 cm. Conglomerates contain well-rounded pebbles of mostly quartzite with subordinate chert and minor limestone. Locally abundant silicified wood was also noted. Sandstones are mineralogically and texturally less diverse than those of the subjacent unit, consisting largely of rounded to well-rounded monocrystalline quartz and chert.

Based on the above observations and evidence for west or northwest paleoflow (Fig. 4), the middle pebbly sandstone unit appears to represent deposits of a west-facing piedmont system that drained an uplifted terrane consisting dominantly of older sedimentary rocks. Interfingering relations with the subjacent axial river deposits of the lower red sandstone unit and near orthogonality of paleoflow indicators between the two units suggest that the axial system was pushed westward by a prograding piedmont represented by the middle pebbly sandstone unit.

Upper conglomerate unit

The upper conglomerate unit consists of conspicuously coarse conglomerate and subordinate medium- to very coarse-grained sandstone (Fig. 5). Maximum clast size is about 50 cm; most clasts are cobble-sized. The clasts consist almost exclusively of Precambrian granite and gneiss with minor amounts of Paleozoic limestone. Associated sandstones are dominated by first-cycle, arkosic detritus.

Bedding in the upper conglomerate unit is lenticular to sheet-like and typically less than about 1.5 m thick. Sedimentary structures are dominantly trough crossbedding and horizontal stratification, although poorly stratified to massive beds are not uncommon. Pebble imbrications indicate that paleotransport was to the south (Fig. 6).

The presence of coarse detritus of Precambrian derivation in the upper conglomerate unit has important tectonic implications. Most Eocene paleogeographic maps for north-central New Mexico place the Galisteo deposits of St. Peter's Dome near the axis of the Galisteo–El Rito basin (cf. Baltz, 1978; Gorham and Ingersoll, 1979; Logsdon, 1981; Ingersoll et al., 1990). These deposits, however, are significantly coarser than any of the Galisteo Formation deposits to the south, and are comparable

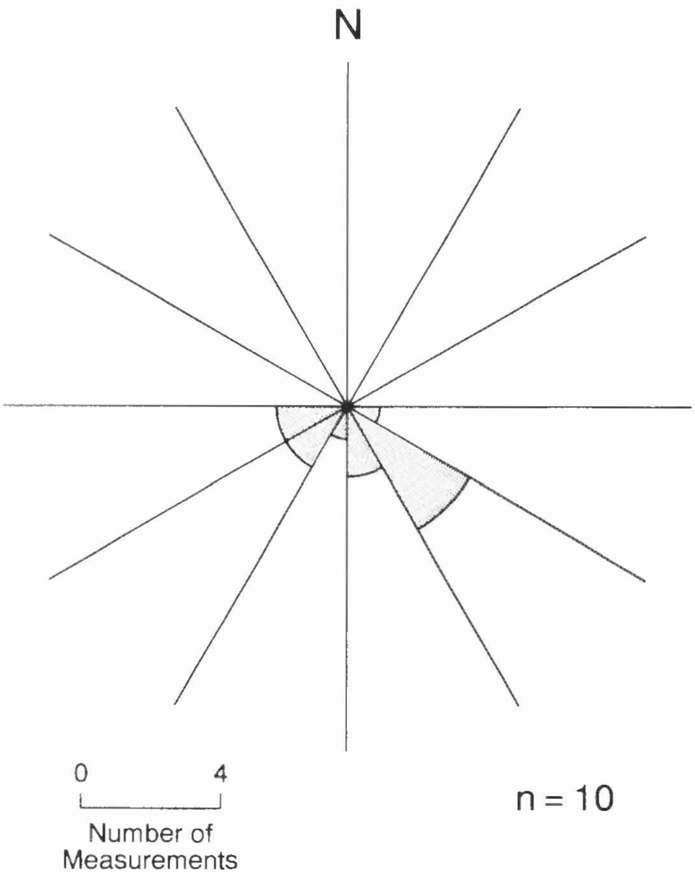

FIGURE 3. Paleocurrent rose diagram for lower red sandstone unit of Galisteo Formation near St. Peter's Dome, based on crossbedding and mudclast imbrications. Each measurement represents the visual average of at least several paleocurrent indicators within a few square meters of outcrop.

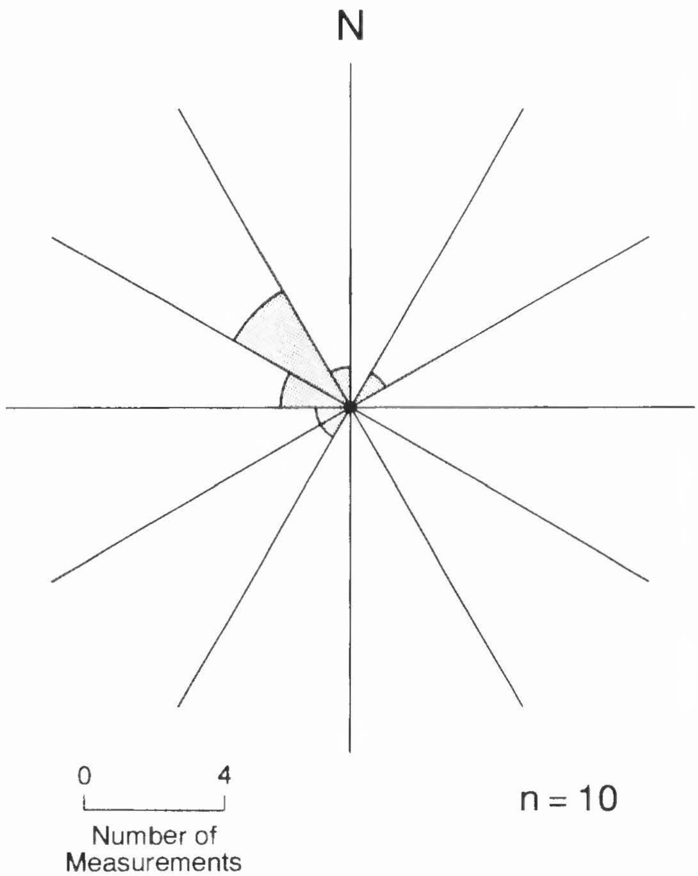

FIGURE 4. Paleocurrent rose diagram for middle pebbly sandstone unit of Galisteo Formation near St. Peter's Dome, based on pebble imbrications.

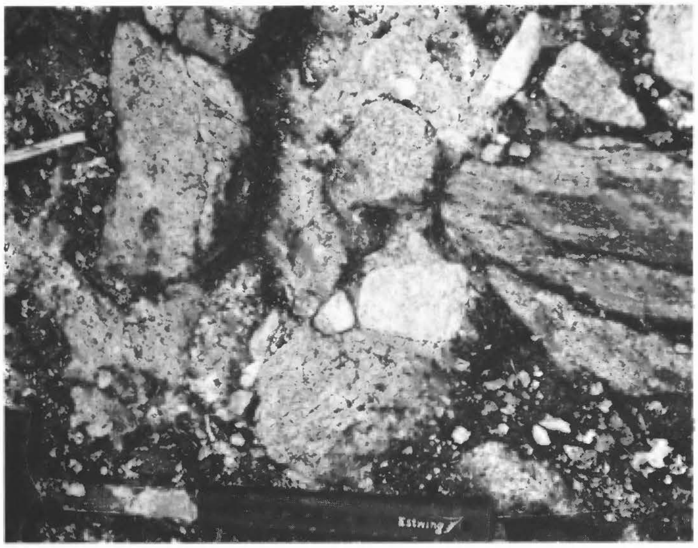

FIGURE 5. Cobbles of Precambrian granite-gneiss in upper conglomerate unit of Galisteo Formation near St. Peter's Dome.

to the conglomerates of the El Rito Formation, where they are exposed directly adjacent to their source areas in the Laramide Brazos uplift. The cobbles and boulders of granite and gneiss in the upper conglomerate unit demand a Laramide uplift nearby (probably within a few kilometers) to the north, in which Precambrian rocks were exposed. Such an area of Laramide basement uplift to the west of the Pajarito fault zone (Fig. 1) is unlikely, as drilling has documented substantial thicknesses (as much as 794 m) of Pennsylvanian and Permian strata beneath the Valles caldera (Nielson and Huler, 1984; Goff et al., in press). The remaining alternative is that basement exposures existed during the Eocene to the east of the Pajarito fault zone, beneath what is now the structurally deepest part of the Española half-graben (i.e., the west-tilted block, within the broader Española Basin, which is bounded by the Pajarito fault zone on the west). Indeed, the coarse detritus within the middle and upper units of the Galisteo Formation near St. Peter's Dome appear to record the unroofing of rising Laramide uplifts to the east and north. The most likely source for the coarse, basement-derived detritus in the upper conglomerate unit was the convex-westward hanging-wall block of the Pajarito fault zone south of Los Alamos (Fig. 7). Such an interpretation requires that the Española half-graben is tectonically inverted from a Laramide upthrusted block (herein termed the Pajarito uplift), a hypothesis that is supported by several other lines of evidence (see below). The structural collapse of Laramide uplifts to form extensional basins has been invoked elsewhere in the Rio Grande rift (Herrick, 1904; Sales, 1983; Cather, 1989, 1990).

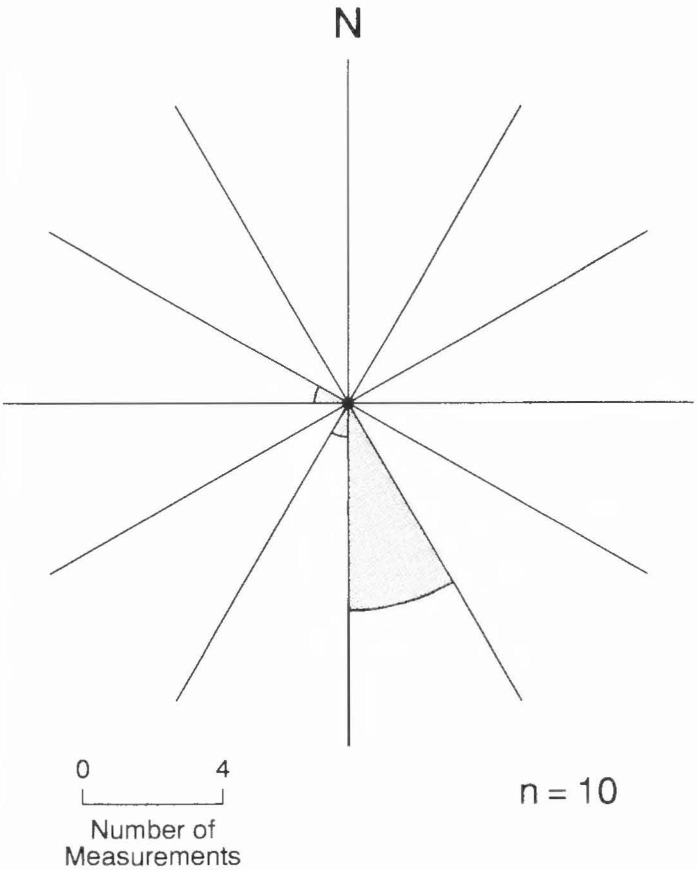

FIGURE 6. Paleocurrent rose diagram for upper conglomerate unit of Galisteo Formation at St. Peter's Dome, based on pebble imbrications.

The exposures at Arroyo Hondo

The deeply incised canyon of Arroyo Hondo about 7 km south-southeast of Santa Fe provides perhaps the most complete exposure of Tertiary deposits within the southern Española Basin. These deposits disconformably overlie Precambrian granite-gneiss and consist, in ascending stratigraphic order, of the Espinaso (Oligocene), Abiquiu (upper Oligocene–lower Miocene) and Tesuque Formations (middle to upper Miocene; see summary of age constraints for these units by Ingersoll et al., 1990). The Espinaso and Abiquiu Formations at Arroyo Hondo have important implications for the tectonic development of the Española half-graben.

The basal Tertiary strata at Arroyo Hondo were tentatively correlated with the Espinaso Formation by Stearns (1953a, b). Spiegel and Baldwin (1963) and Kelley (1978), however, correlated these same rocks with the Galisteo Formation despite the predominance of volcanogenic detritus and lavas in the unit. Baldridge et al. (1980) dated a latite flow in the upper part of the sequence at 29 Ma. Smith et al. (1991) subsequently correlated the basal Tertiary rocks at Arroyo Hondo with the upper, alkaline part of the Espinaso on the basis of lithology.

In addition to minor amounts of Precambrian detritus scattered throughout much of the Espinaso section at Arroyo Hondo, a distinctive sequence of entirely nonvolcanic strata about 15 m thick intervenes between the Precambrian basement and the overlying volcaniclastic beds. These nonvolcanic strata consist almost entirely of Precambrian-derived detritus, although rare clasts of Paleozoic limestone were occasionally noted. Maximum clast size is about 20 cm. It is possible that these nonvolcanic beds correlate with the Eocene Galisteo Formation, but evidence suggests that these beds more likely represent an episode of Oligocene deposition induced by the local onlap of the upper, alkaline part of the Espinaso Formation (30–28 Ma; see summary in Smith et al., 1991) across the beveled core of a Laramide basement uplift. The basal 3–5 m of the nonvolcanic beds appear to be colluvial in origin, but are overlain by distinctly fluvial, Precambrian-clast-dominated beds that compose the remainder of the sequence. These fluvial beds show evidence of south-southeast paleoflow (Fig. 8), and are overlain conformably by a fine-grained interval about 20 m thick, in which the transition to dominantly volcaniclastic detritus occurs. The fine-grained unit, in turn, is gradationally overlain by conglomeratic volcaniclastic deposits that record easterly paleoflow (Smith et al., 1991, p. 88). The mixed provenance of the fine-grained unit and the convergence in paleoflow between the subjacent and superjacent conglomeratic units supports a depositional scenario in which a prograding volcaniclastic apron of late Espinaso age lapped eastward onto relict Laramide highlands, pushing a fine-grained axial system and opposing Precambrian-dominated piedmont system ahead of it.

Despite the probable post-Laramide age of the basal nonvolcanic strata at Arroyo Hondo, these beds provide valuable insight into early Tertiary paleogeography of the area. Paleocurrent and clast composition

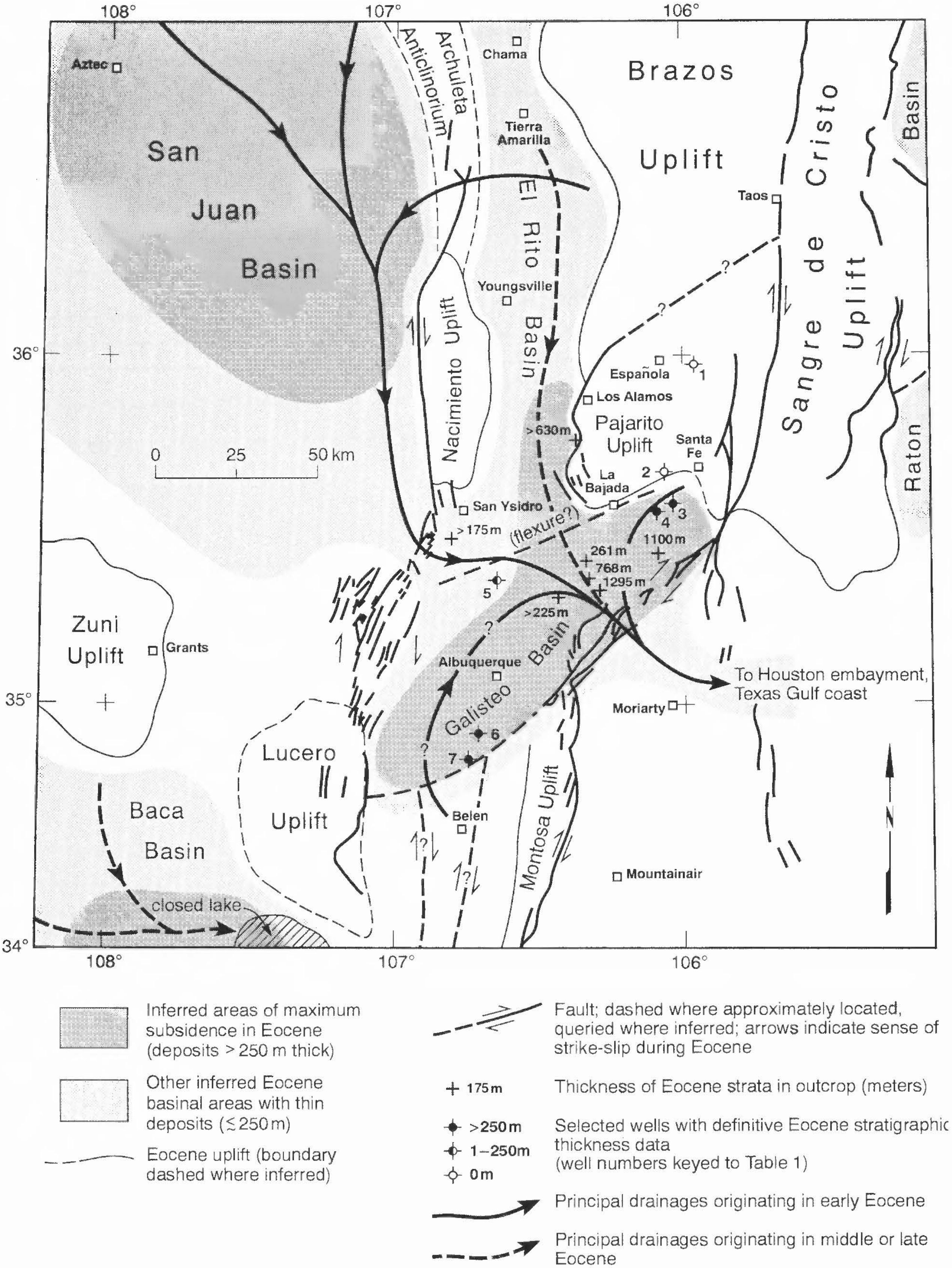

FIGURE 7. Late Laramide (Eocene) paleotectonic map showing proposed geometry of basins and uplifts, selected faults, principal Eocene paleodrainages, and thickness control-points of Eocene rocks in the Galisteo basin–Pajarito uplift area. Thickness of Eocene rocks in the San Juan Basin is speculative due to erosive upper contact of Eocene strata in this area. See text for discussion. Map area is same as Fig. 1. NOTE: Fig. 7 and Table 1 list only those wells for which the presence or absence of Eocene strata can be definitively demonstrated. Wells for which the Tertiary stratigraphy is ambiguous or was not recorded are not shown. Also some wells in the Hagan embayment area that contain Eocene strata are omitted for sake of clarity.

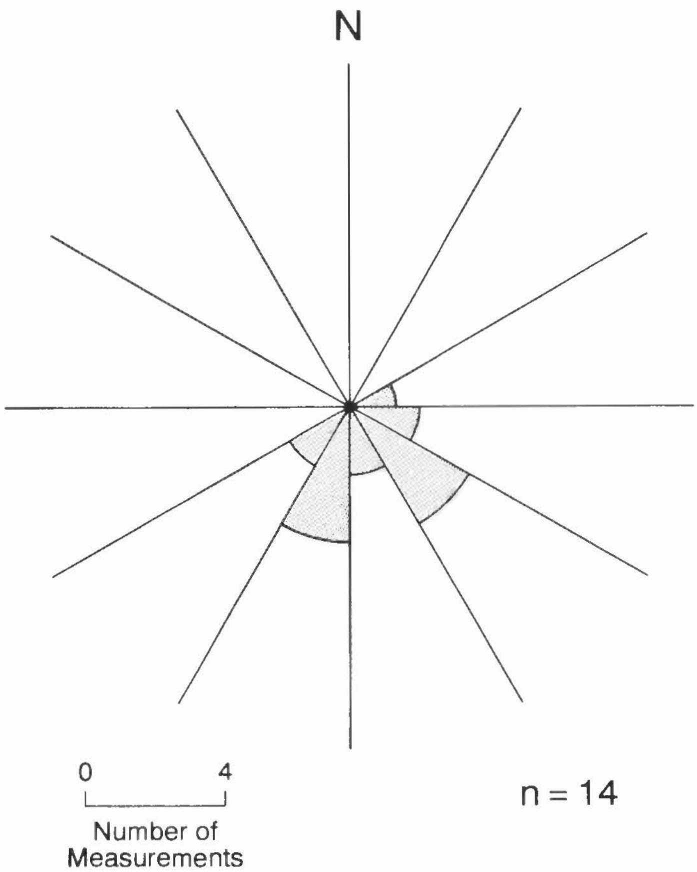

FIGURE 8. Paleocurrent rose diagram for basal nonvolcanic strata (upper Oligocene?) at Arroyo Hondo, based on pebble imbrications.

data indicate that major Precambrian exposures were extant to the north-northwest, *within* what is now the Española Basin. Furthermore, evidence for south-southeast paleoflow indicates these source regions were topographically, and possibly structurally, higher than the Laramide basement exposures in the southernmost part of the Sangre de Cristo Range. That the Sangre de Cristo Range was a Laramide positive area is indisputable, as shown by diverse structural and stratigraphic data (e.g., Baltz, 1978; Gorham and Ingersoll, 1979) and fission-track cooling ages (Kelley, 1990). The exposures at Arroyo Hondo provide another line of evidence that an area of Laramide uplift (the Pajarito uplift) extended southwestward beneath what is now the Española half-graben (Fig. 7).

The Espinaso Formation at Arroyo Hondo is disconformably overlain by about 150 m of dominantly volcaniclastic strata of the Abiquiu Formation (Stearns, 1953a; these strata were termed Bishops Lodge Member of Tesuque Formation by Spiegel and Baldwin, 1963), which are, in turn, overlain by the Precambrian-derived clastics of the main body of the Tesuque Formation. Pebble imbrication in the Abiquiu shows northwest paleotransport. This observation, in concert with evidence for northerly paleoflow in the Abiquiu exposures in the Hagan area to the south (Stearns, 1953a, p. 472) represent the earliest geological evidence for development of systematic northerly regional paleoflow, in contrast to the generally southerly Eocene paleoflow (e.g., Gorham and Ingersoll, 1979) and complex radial paleodrainage during Espinaso time (Kautz et al., 1981; Smith et al., 1991). The tectonic significance of these relations will be discussed below.

Subsurface geology

Although the stratigraphy of Neogene rocks in the Española Basin has been extensively studied, knowledge of the subsurface distribution of older rocks is limited by the scarcity of well penetrations in this area. It has long been known that post-Laramide deposits directly overlie Precambrian and local Pennsylvanian rocks throughout the eastern and northern parts of the basin. In contrast, a thick sequence of Paleogene, Mesozoic and Paleozoic strata are preserved to the south within the Galisteo basin.

The geologic literature contains diverse interpretations of the nature and position of the northward pinchout of the thick Eocene and older strata that crop out to the south of the Española Basin. Based largely on surficial geology, Kelley (1978) interpreted the northward pinchout of Eocene and older rocks to be north of Santa Fe, within the central part of the Española Basin. In 1984, Black published segments of five seismic reflection lines from the southern and central Española Basin, although the precise location of these lines remains proprietary. Black (1984) interpreted the presence of possible Paleozoic strata within a Laramide thrust plate on the basis of these seismic data. Subsequent drilling of the Yates Petroleum no. 2 La Mesa Unit about 10 km west of Santa Fe (Fig. 7; Table 1) demonstrated, however, that the "possible Paleozoic strata" reported by Black (1984) are in fact a 460-m-thick sequence of interbedded lacustrine limestones and clastic rocks of Tertiary age (unpubl. report by Black Oil, Inc. for Yates Petroleum Corporation). This same report indicates that the pinchout of basal Paleozoic strata occurs a few kilometers south of the aforementioned well, thus indicating that Precambrian basement was exposed on the Pajarito uplift about 10 km west-southwest of Santa Fe.

The age and correlation of the interbedded Tertiary limestones and clastic rocks penetrated by the Yates Petroleum no. 2 La Mesa Unit west of Santa Fe are of critical importance to the interpretation of the Cenozoic geologic history of the Española Basin area. These beds have been informally termed the "La Mesa lake(?) sequence" and assigned a nonspecific Tertiary age on the basis of fossil bone and wood fragments encountered during drilling (NMOCD, 1986). In their geophysical model for the Española Basin, Biehler et al. (1991) considered the La Mesa lake(?) sequence to be Eocene, based on perceived similarities to the Galisteo and El Rito Formations. Recently obtained drilling records for the Yates Petroleum no. 2 La Mesa Unit (on file at New Mexico Library

TABLE 1. Thickness of Eocene strata in selected wells in the Albuquerque–Santa Fe area (data from Lozinsky, 1988 and New Mexico Library of Subsurface Data, NMBMMR). Well numbers are keyed to Fig. 7.

Well Number	Name	Thickness (m)
1.	Castell and Wigzell no. 1 Kelly Federal	0
2.	Yates Petroleum no. 2 La Mesa Unit	0
3.	Yates Petroleum no. 3 La Mesa Unit	427
4.	J. Gianardi no. 1 CKZ	451
5.	Shell Santa Fe Pacific no. 1	205
6.	Shell Isleta no. 2	288
7.	Shell Isleta Central no. 1	454

of Subsurface Data, NMBMMR) clearly indicate, however, that the La Mesa lake(?) sequence is post-Eocene. The mud log by W. B. Noles Co. contains no less than 20 references to volcaniclastic rocks scattered throughout the sequence; such lithologies are essentially absent in the Galisteo and El Rito Formations. Stephen Speer, who was the well-site geologist for Yates Petroleum during drilling of the well, has confirmed the presence and abundance of volcanogenic, commonly vitric, detritus in the La Mesa lake(?) sequence (oral comm. 1991). Furthermore, based on their mode of preservation, the fossil fragments retrieved during drilling probably pertain to the Santa Fe Group (S. G. Lucas, oral comm. 1991).

Additional evidence against the presence of Eocene and older strata in the subsurface of the Española half-graben is provided by cuttings from the Castell and Wigzell no. 1 Kelley Federal well about 32 km north of Santa Fe (Fig. 7; Table 1), which indicate that Precambrian-dominated detritus of the Tesuque Formation disconformably overlies Pennsylvanian limestone in that area (cuttings on file at New Mexico Library of Subsurface Data, NMBMMR). Stratigraphy in wells south of the Santa Ana accommodation zone, however, differ markedly from those wells in the Española half-graben. South of the accommodation zone, all wells for which Tertiary stratigraphic data exist show substantial thicknesses of Galisteo strata (Fig. 7) overlying thick sequences of Mesozoic rocks. Similar stratigraphic relations are present in outcrops to the south in the Cerrillos and Hagan embayment areas.

Inasmuch as the northward pinchout of Eocene and older strata onto the Pajarito uplift spatially coincides with the general area of stratal-tilt reversal to the south of the Española half-graben, I suggest that these geologic features share a common heritage. Although the presence of a structural zone between the east-tilted rocks of the northern Albuquerque Basin and Hagan embayment and the west-tilted strata to the north has been recognized for some time (e.g., Kelley, 1979; Chapin, 1988), the kinematics and the precise geometry of the accommodation zone remain obscure. It seems clear that the Santa Ana accommodation zone does not closely resemble the Embudo or Tijeras zones, where opposing stratal tilts are accommodated along narrow zones of strike-slip faulting (Muehlberger, 1979; Russell and Snelson, 1990), but is more akin to the broad accommodation zone at Socorro where complex scissors-like displacement across en echelon, north-trending faults has been documented (Chapin, 1989; see Faulds et al., 1990 for a similar example from elsewhere in the Basin and Range province). Probably the best example of this structural style along the Santa Ana accommodation zone comes from exposures in the Santa Ana Mesa area (about 45 km north of Albuquerque), where several faults change sense of displacement along strike (e.g., Smith et al., 1970). To the north of Santa Ana Mesa beds dip generally west; to the south of the mesa they dip east. Because of poor exposure and probable complex geometry of the zone, depiction of the Santa Ana accommodation zone in Fig. 1 is only an approximation.

Borehole and outcrop data suggest that Phanerozoic strata pinch out northward onto the Laramide Pajarito uplift across a structural zone approximately coincident with the Santa Ana accommodation zone, and that Laramide basement exposures extended westward, at least locally, to the Pajarito fault zone (Fig. 7). Evidence for a Laramide precursor to that part of the Santa Ana accommodation zone to the southwest of the Pajarito uplift, however, is sparse. Although few thickness data exist for the Galisteo Formation near the accommodation zone, southward thickening of Eocene strata beneath the northern Albuquerque Basin (Fig. 7; Lozinsky, 1988) suggest the accommodation zone may have acted as a flexural hinge for the southeast-tilted floor of the Galisteo basin.

Correlation and implications of the La Mesa lake(?) sequence

The La Mesa lake(?) sequence penetrated by the Yates Petroleum no. 2 La Mesa Unit is herein correlated with the Abiquiu Formation (or equivalent Bishops Lodge Member of Tesuque Formation) based on the following lines of reasoning:

1. *Presence of abundant volcanogenic detritus.* This argues conclusively against correlation with the Eocene Galisteo Formation and the main body of the Miocene Tesuque Formation, both of which are dominated by nonvolcanic materials. The contact between the Precambrian-derived Tesuque Formation and the largely volcaniclastic Abiquiu occurs at a depth of about 3960 ft (1207 m) in the well, and the base of the Abiquiu where it overlies the Precambrian occurs at a depth of 7534 ft (2297 m). Thus the Abiquiu in the well is about 1090 m thick, the basal 640 m of which contains limestone beds and constitutes the La Mesa lake(?) sequence.
2. *Presence of vitric volcaniclastic detritus.* Despite the occurrence of a thick sequence of Espinaso beds at Arroyo Hondo, about 13 km southeast of the Yates Petroleum no. 2 La Mesa Unit, correlation of the La Mesa lake(?) sequence with the Espinaso can probably be ruled out. The vitric volcaniclastic detritus described in the mud log and by the well-site geologist for the La Mesa lake(?) sequence differs from the Espinaso, which contains almost entirely lithic detritus (Kautz et al., 1981; Smith et al., 1991; G. A. Smith, personal comm. 1992). Vitric detritus, however, is common in the Abiquiu Formation (Vazzana, 1980; Vazzana and Ingersoll, 1981), and was probably derived from the voluminous pyroclastic eruptions of late Oligocene–early Miocene age in the San Juan Mountains area to the north (cf. Ingersoll et al., 1990; Ingersoll and Cavazza, 1991).
3. *Presence of limestone.* The occurrence of lacustrine limestone beds in the Abiquiu Formation exposures near La Bajada, about 32 km southwest of Santa Fe (Stearns, 1953a), and in the La Mesa lake(?) sequence support correlation of these units. The limestone beds near La Bajada are as much as 5 m thick and are associated with thick tuffaceous deposits also of probable lacustrine origin (Stearns, 1953a). Thickness of individual limestone beds in the La Mesa lake(?) sequence (estimated from electric logs available from New Mexico Library of Subsurface Data, NMBMMR) averages about 1.5 m and ranges up to about 5 m. The above occurrences represent the only known associations between thick lacustrine limestones and volcaniclastic deposits in the southern Española Basin.

If a lacustrine depocenter of Abiquiu age existed in the southern Española Basin, what was it geographic extent? As noted above, the northerly paleocurrents indicated by Abiquiu exposures at Arroyo Hondo and in the Hagan area represent the earliest geological evidence for systematic drainage reversal from the generally southward Laramide paleodrainage, and support the possibility of centripetal (closed) drainage during Abiquiu time. The prominent, laterally continuous reflectors imaged seismically and interpreted by Black (1984) to represent Paleozoic limestones in a possible overthrust plate are now known to be limestones of the La Mesa lake(?) sequence, herein correlated with the Abiquiu Formation. Many of these reflectors are laterally quite extensive (Black, 1984, figs. 3, 6), although actual dimensions are unknown due to lack of scale and the proprietary location of the seismic lines. Biehler et al. (1991) published a geophysical model for the east-central Española half-graben along a transect that trends east-northeast through Tesuque Pueblo, about 13 km north of Santa Fe. The basal Tertiary unit in the reflection profile contains prominent, laterally continuous reflectors that Biehler et al. (1991) correlated with the La Mesa lake(?) sequence, although they regarded the sequence to be part of the Galisteo Formation. If these reflectors, in fact, pertain to the Abiquiu Formation, then the limestone-bearing part of the Abiquiu lacustrine system occupied much of the southern Española half-graben, from La Bajada northeastward nearly to Santa Fe and Tesuque Pueblo. Contact relations at St. Peter's Dome (see below) indicate the Abiquiu lacustrine rocks did not extend westward beyond the Pajarito fault zone. The northern boundary of the lacustrine system is poorly constrained, however, and the eastern part of the lake system may include noncalcareous playa beds, such as those described north-northeast of Santa Fe by Boyer (1959).

Ingersoll et al. (1990) depicted the Abiquiu depositional basin to extend westward to the Nacimiento uplift. Several lines of evidence, however, indicate the Pajarito fault zone was tectonically active during Abiquiu time, and that the footwall of the fault zone was at least locally emergent:

1. *Contact relations at St. Peter's Dome.* As noted above, a thin sequence of Santa Fe Group disconformably overlies the Galisteo

Formation with 20°–30° of angular discordance near St. Peter's Dome (Goff et al., 1990) and contains a 16.5 ± 1.4 Ma basalt flow near its base (Gardner and Goff, 1984). This basalt date and the radiometric ages for the basal part of the overlying Keres Group volcanics (10–12 Ma; see summary in Goff et al., 1990) constrain the age of these Santa Fe exposures to be largely middle Miocene (Barstovian), and support previous correlations of these exposures with the Tesuque Formation (Kelley, 1978) and the middle Santa Fe Group (Goff et al., 1990). The angular unconformity between the Santa Fe Group and the underlying Galisteo Formation at St. Peter's Dome indicates significant westward tilting and erosion of the footwall of the Pajarito fault zone *prior to* the middle Miocene. Although these contact relations do not rule out deformation during Espinaso time, they are more plausibly related to Abiquiu-age tilting and subsidence in the Española half-graben to the east.

2. *Westward thickening of reflectors in Española half-graben.* Geophysical data for the east-central Española half-graben indicate westward thickening of all Tertiary units, including the La Mesa lake(?) sequence, in the subsurface (Biehler et al., 1991). If the proposed correlation with the Abiquiu is correct, then the westward thickening of the La Mesa lake(?) sequence implies that westward tilting of the area was under way as early as late Oligocene–early Miocene time. Maximum thickness of the La Mesa lake(?) sequence in the central Española half-graben (about 1200 m; Biehler et al., 1991) far exceeds that of the Abiquiu Formation near its type locality to the northwest (<310 m; Vazzana and Ingersoll, 1981). The probable occurrence of nonlacustrine Abiquiu strata above the La Mesa lake(?) sequence, as is present in the Yates Petroleum no. 2 La Mesa Unit and in the Abiquiu exposures near La Bajada (Stearns, 1953a, p. 470), may increase the total thickness of Abiquiu in the central Española half-graben beyond 1200 m. These thickness data suggest that the principal depocenter for the Abiquiu Formation was within the Española half-graben. Contact relations exposed at St. Peter's Dome indicate that the thick Abiquiu section in the Española half-graben did not extend westward beyond the Pajarito fault zone, and that the footwall block of the fault zone experienced uplift, erosion and westward tilting at least locally during Abiquiu (or possibly Espinaso) time.

The above relations strongly suggest that half-graben development and down-to-the-east displacement along the Pajarito fault zone was under way as early as the late Oligocene–early Miocene. This timing is compatible with early deformation in other basins of the Rio Grande rift (e.g., Chapin, 1988), but is older than the middle to late Miocene age envisioned by many workers in the Española Basin. Evidence for early rift subsidence and development of closed drainage to the east of the Pajarito fault implies significant local structural control on deposition of the Abiquiu Formation, as opposed to simple aggradation of early rift volcaniclastic aprons as advocated by Ingersoll and others (1990). Furthermore, if the entire thickness of Tertiary strata (about 3 km) in the geophysical model of Biehler et al. (1991) is assigned to the Santa Fe Group, the maximum thickness of rift-related sediments in the Española Basin becomes comparable to that of the Albuquerque Basin (3–4 km; Lozinsky, 1988, fig. 8-4) and the San Luis Basin (about 4 km; Brister, 1990, p. 129). In their original interpretation of the geophysical data from the east-central Española half-graben, Biehler et al. (1991) assigned a maximum thickness of only about one kilometer to the Santa Fe Group; by my analysis this is less than half the thickness of Santa Fe present in the nearby Yates Petroleum no. 2 La Mesa Unit well.

SOUTHEAST BOUNDARY OF THE GALISTEO BASIN

Tijeras fault zone

A major northeast-trending set of prominent faults, including the Tijeras, Gutierrez, San Lazarus, Los Angeles and Lamy faults (Stearns, 1953a; Kelley and Northrop, 1975; Lisenbee et al., 1979), are exposed to the east of Albuquerque; for brevity, these are collectively referred to herein as the Tijeras fault zone (Fig. 1). The Tijeras fault zone continues southwestward beneath the Albuquerque Basin where it forms the Neogene accommodation zone between the east-tilted rocks of the northern Albuquerque Basin and west-tilted strata to the south (Lozinsky, 1988; Russell and Snelson, 1990). The Tijeras zone has experienced a long and complex kinematic history, including episodes of strike-slip (Lisenbee et al., 1979). Kelley and Northrop (1975) documented perhaps as much as 3 km of net post-Cretaceous left-lateral slip along the Tijeras fault zone; such deformation is expectable in view of the greater amount of Neogene extension that occurred to the north of the zone (i.e., Hagan embayment and adjacent areas). Laramide strike-slip along the Tijeras zone, however, was probably right lateral (Lisenbee et al., 1979, p. 96). Although both normal and reverse separation occurs along individual faults within the Tijeras fault zone, Stearns (1953a, p. 491) observed that "most faults are steep and generally normal." The dip-slip component of Laramide displacement across the Tijeras fault zone was systematically down to the northwest, as shown by stratigraphic data and fission-track cooling ages (see below). The faults of the Tijeras zone appear to compose the southeast boundary of the Galisteo basin throughout their extent.

Invocation of the Tijeras zone as the southeastern boundary of the Galisteo basin is not a new idea. Pronounced southeastward thickening of Galisteo outcrops in the Hagan embayment area (Fig. 7) has been noted by previous workers (Stearns, 1943; Gorham, 1979; Gorham and Ingersoll, 1979) and has been tentatively interpreted by Ingersoll et al. (1990) to be the result of subsidence northwest of the Tijeras zone. Northwestward paleoflow in the upper Galisteo Formation exposures near the Tijeras fault zone (Gorham, 1979) supports this interpretation (see Ingersoll et al., 1990, fig. 3B). Increased mudstone/sandstone ratios in the Galisteo exposures near the fault zone (Gorham and Ingersoll, 1979, fig. 2) also support the concept of increased subsidence toward the southeast (cf. Leeder and Gawthorpe, 1987). Near the northeast end of the basin, the thickness of the Galisteo more than doubles from the Yates Petroleum no. 3 La Mesa Unit (427 m) and J. Gianardi no. 1 CKZ (451 m) wells to the 1100 m exposed near Cerrillos to the south (Lucas, 1982) (Fig. 7; Table 1).

Lozinsky (1988) interpreted a Laramide precursor to the Tijeras accommodation zone (Fig. 1) to have divided Eocene drainages in the Albuquerque Basin area. In the northern Albuquerque Basin, Eocene strata thicken southward toward the Tijeras accommodation zone (Fig. 7; Table 1; Lozinsky, 1988), although this thickening is not as pronounced as in the Hagan embayment area. To the south of the accommodation zone, Eocene deposits appear to be thin or absent. Chapin and Cather (1981) and Cather and Johnson (1984, 1986) interpreted the presence of Eocene deposits in the southern Albuquerque Basin (the northern part of their Eocene Carthage–La Joya basin) based on well penetrations described by Foster (1978). These well data and others were subsequently re-evaluated by Lozinsky (1988) who found no definitive evidence for the presence of Eocene strata in the subsurface of the southern Albuquerque Basin. Based on their interpretation of industry seismic-reflection data and borehole penetrations, Russell and Snelson (1990) also found no evidence for Eocene deposits south of the Tijeras accommodation zone. It appears that the southern Albuquerque basin was mildly positive during the Eocene. The area is now thought to be characterized stratigraphically by Mesozoic strata overlain by mid-Tertiary volcaniclastic rocks or by beds of the Santa Fe Group (Lozinsky, 1988; Russell and Snelson, 1990).

Throughout most of its extent, the Tijeras zone today bounds a structurally low area to the northwest (e.g., Russell and Snelson, 1990, fig. 8; Kelley and Northrop, 1975, fig. 67), a situation that probably has prevailed since the Eocene. The principal exception to this rule is where the Tijeras fault passes between the modern Sandia and Manzano ranges. There, the northern block (Sandia Mountains) is structurally higher than the block to the south. It seems likely, however, that this is purely a Neogene effect and that the fault was down to the northwest during the Eocene. Fission-track cooling ages for the Manzano and Los Piños ranges indicate an episode of Laramide uplift and cooling to the south of the Tijeras fault, whereas fission-track data for the Sandia Mountains record only Neogene, not Laramide, uplift and cooling (Kelley and Duncan, 1986; Kelley and Chapin, 1990; Kelley et al., in press). It is probable that this local up-to-the-northwest aspect of the modern Tijeras fault is related to isostatic rebound of the footwall (Sandia Mountains block) due to tectonic denudation along major west-dipping faults in the northern Albuquerque basin.

A similar, but kinematically more obscure, reversal of the Laramide down-to-the-northwest displacement along the Tijeras accommodation zone also may be occurring. Although the northern Albuquerque basin today remains structurally lower than the basin to the south (Lozinsky, 1988; Russell and Snelson, 1990), the more deeply incised nature of the Rio Grande in the northern basin implies that up-to-the-north displacement across the accommodation zone has occurred at least since the middle or early Pleistocene. This relation can be seen from Interstate 25 north of Los Lunas, near the confluence of Hells Canyon (which is incised along the approximate trace of the Tijeras accommodation zone) and the Rio Grande. North of the confluence, the Rio Grande is more deeply incised below the high surface in the eastern basin (Llano de Manzano surface of Machette, 1978) than it is in areas to the south. To the southwest, Kelley (1977, fig. 9) depicted a significant down-to-the-south step in the Ortiz surface (now correlated with the younger Llano de Albuquerque surface; Machette, 1978) on Ceja Mesa, where it crosses the accommodation zone in the southern part of T7N.

Laramide Montosa uplift

The existence of a Laramide positive area in the vicinity of the modern Sandia, Manzano and Los Pinos Mountains (Fig. 7) has been proposed by several workers (Eardley, 1962; Kelley and Northrop, 1975; Kelley, 1977). This uplift was termed the Sandia uplift by Chapin and Cather (1981) and Cather and Johnson (1984, 1986), a name that is now a misnomer because it appears that the modern Sandia Mountains were probably not involved in the Laramide uplift. The Sandia Mountains exhibit no evidence of Laramide cooling (Kelley and Duncan, 1986) and stratigraphic evidence from the Placitas area in the northern part of the range favors only mild erosion prior to Eocene deposition, where the base of the Galisteo Formation disconformably overlies the Upper Cretaceous Menefee Formation (Menne, 1989). In the Manzano and Los Piños Mountains to the south, however, fission-track cooling ages indicate Paleocene-Eocene uplift (Kelley and Chapin, 1990; Kelley et al., in press), probably related to convergent right-lateral deformation along the Montosa fault (Fig. 1; Hayden, 1991). Because of these relations, the term Montosa uplift is herein proposed to encompass that part of the former Laramide Sandia uplift to the south of the Tijeras fault zone. East of Belen (Fig. 1), conglomerates of the Baca Formation on the Hubble bench are dominated by fragments of the Permian Abo Formation, indicating moderately deep erosion on the Laramide Montosa uplift to the east (Cather and Johnson, 1984, 1986). Correlation of these conglomerates with the Baca Formation, however, has been questioned by Lozinsky (1988, p. 128), who regards them as possibly Santa Fe Group.

EOCENE BASIN GEOMETRIES AND PALEODRAINAGE

Fig. 1 summarizes the mean paleocurrent vectors for Eocene deposits in north-central New Mexico based on previous studies (Smith, 1988; Brister, 1990; Logsdon, 1981; Gorham and Ingersoll, 1979; Cather and Johnson, 1984, 1986) and new data from this study for the Arroyo Hondo (probably post-Eocene paleoflow) and St. Peter's Dome areas. Fig. 7 shows the principal Eocene paleodrainage net inferred from those paleocurrent vectors and the basin geometries described in this report. The paleodrainages are divided into two types (Lucas, 1984), those that originated in the early Eocene and others that developed in middle or late Eocene. Because thick lacustrine deposits have not been reported in the Galisteo Formation, the Eocene paleodrainage is presumed to have exited the Galisteo basin to the southeast, toward the Gulf of Mexico (e.g., Cather, 1991). The interpretations shown in Fig. 7 differ from analyses of previous workers in three significant ways:

1. The El Rito basin is bowed to the west around the proposed Pajarito uplift. This modification to the basin geometry does not violate any published paleocurrent or stratigraphic data other than those reinterpreted above.
2. The northwestern margin of the structurally deep Galisteo basin may be delimited by an ill-defined flexure along a Laramide precursor to the Santa Ana accommodation zone. The northeast part of this flexure also defines the southern boundary of the Pajarito uplift.
3. The southeast-tilted Galisteo basin is extended to the southwest to include the modern Sandia Mountains and Albuquerque basin areas to the north of the Tijeras fault zone. The paleodrainage depicted in the southwest part of the Galisteo basin, is, of course, purely speculative.

TECTONIC SYNTHESIS

Numerous basins developed during the Eocene in the southern Rocky Mountains. Most of these basins trend north-northwest and were formed by right-lateral transpressional deformation along the eastern boundary of the Colorado Plateau as it impinged north-northeastward against the craton during the late Laramide (Chapin and Cather, 1981). Right-lateral oblique- or strike-slip faults of late Laramide age have been documented or inferred by numerous workers in the southern Rocky Mountains (Fig. 9). At the latitude of Española in northern New Mexico such faults are distributed across a broad zone about 320 km wide, and include the Hogback-Defiance monocline system of eastern Arizona and western New Mexico (Kelley, 1967; Taylor and Huffman, 1988), the Nacimiento fault (Baltz, 1967), the Picuris-Pecos fault (Miller et al., 1963; Chapin and Cather, 1981), and the frontal faults of the southern Sangre de Cristo Mountains near Mora (O'Neill, 1990, p. 198) (Fig. 9). To the south, right-lateral deformation of probable Laramide age has been described along the Rio Puerco fault zone (Slack, 1975; Slack and Campbell, 1976), the Tijeras zone (Lisenbee et al., 1979, p. 96), and Montosa fault (Hayden, 1991), and conjugate strike-slip and reverse faulting have been reported in the Navajo Gap area north of Sierra Ladron (Hammond, 1987). Also depicted in the southern Albuquerque Basin are two hypothetical strike-slip faults (Figs. 7, 9) that trend northward from the wrench-related Laramide Sierra uplift in the Socorro area (Cather, 1983; Cather and Johnson, 1984, 1986). With the exception of the oblique normal faults of the Rio Puerco fault zone and the Tijeras zone, most of the major faults depicted in Fig. 9 show evidence of oblique reverse slip during the Laramide. The relative importance of strike-slip vs. dip-slip along most of these faults, however, is poorly constrained.

The Galisteo basin is unique among Eocene basins of the southern Rocky Mountains in that it trends northeast, subparallel to the late Laramide σ_1 orientation (Fig. 9; Chapin and Cather, 1981). The basin occupies a major dextral step in the right-lateral convergent wrench-fault system of the Laramide southern Rocky Mountains, where the main deformational front in the southern Albuquerque Basin area steps east to the Sangre de Cristo Range. This geometry suggests that the Tijeras fault zone may have acted as a releasing bend in the Laramide wrench-fault system, a hypothesis that is supported by the dominance of normal faults along the Tijeras zone (Stearns, 1953a, p. 491). Crustal extension adjacent to a releasing bend in the Galisteo basin area may also explain the north-northeast-trending normal faults of the Rio Puerco fault zone (Fig. 9), which are the only major en echelon normal faults of Laramide age known in the southern Rocky Mountains. The normal faults of the Rio Puerco fault zone give way to north-northwest-trending en echelon folds directly north of the proposed releasing bend in the eastern San Juan Basin (Baltz, 1967; Slack and Campbell, 1976), indicating a return to transpressional conditions. In the context of regional Laramide deformation, the Galisteo basin is perhaps best modeled as a southeast-tilted half-graben localized by releasing-bend subsidence along the Tijeras fault zone, which defined the southeast margin of the basin. Although rocks of the Galisteo and El Rito Formations appear to share a common depositional basin, the deeply subsided, northeast-trending Galisteo basin is structurally distinct from the El Rito basin (Figs. 7, 9).

Fig. 10 shows schematic cross sections through differing structural domains within the Laramide southern Rocky Mountains. Cross section A-A′ illustrates the style of convergent wrench faulting that predominated along much of the eastern boundary of the Colorado Plateau

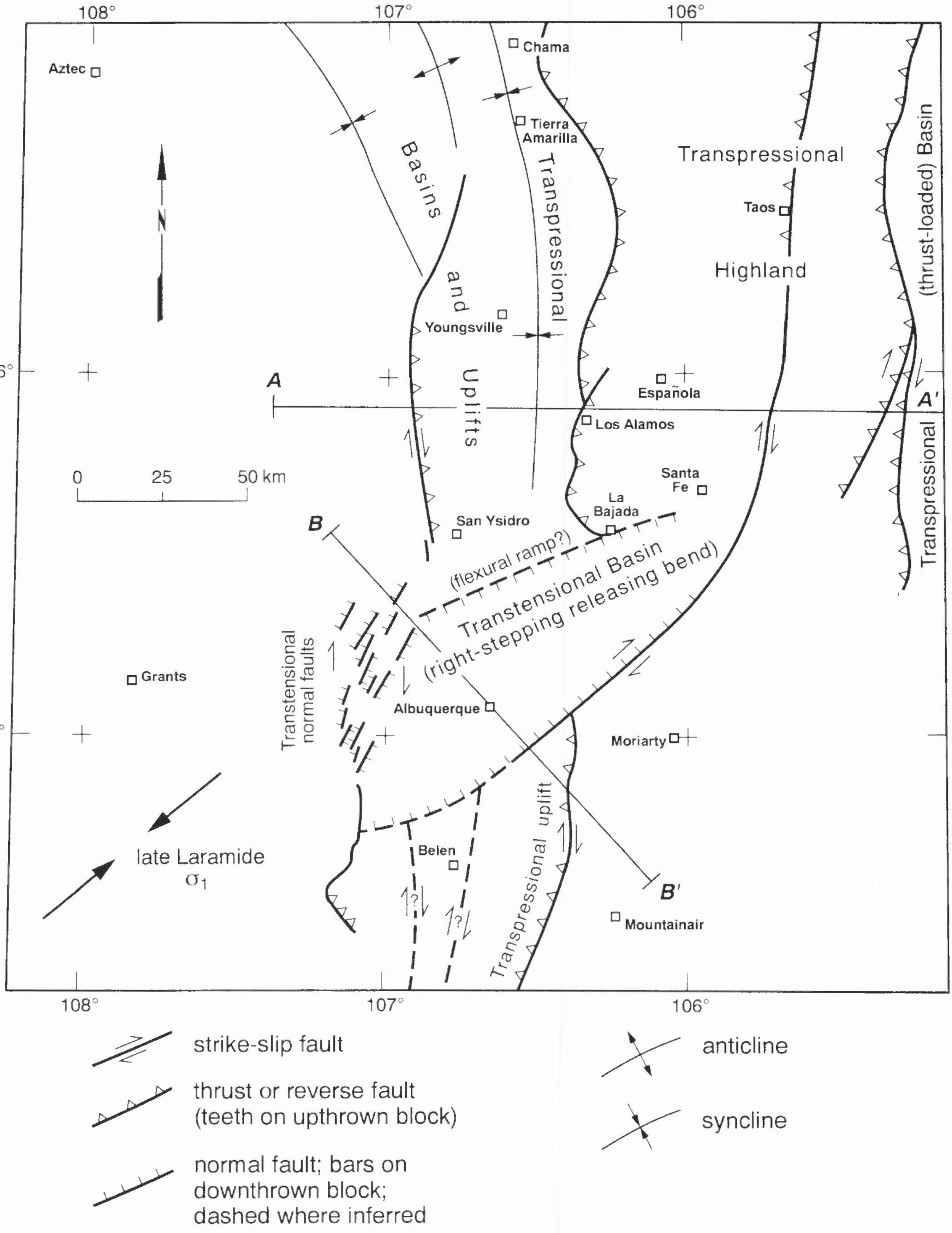

FIGURE 9. Simplified structural map showing major Laramide structural features and interpretation of their origin (see text for discussion). Cross sections along lines A-A′ and B-B′ are depicted in Fig. 10. Map area same as Figs. 1 and 7.

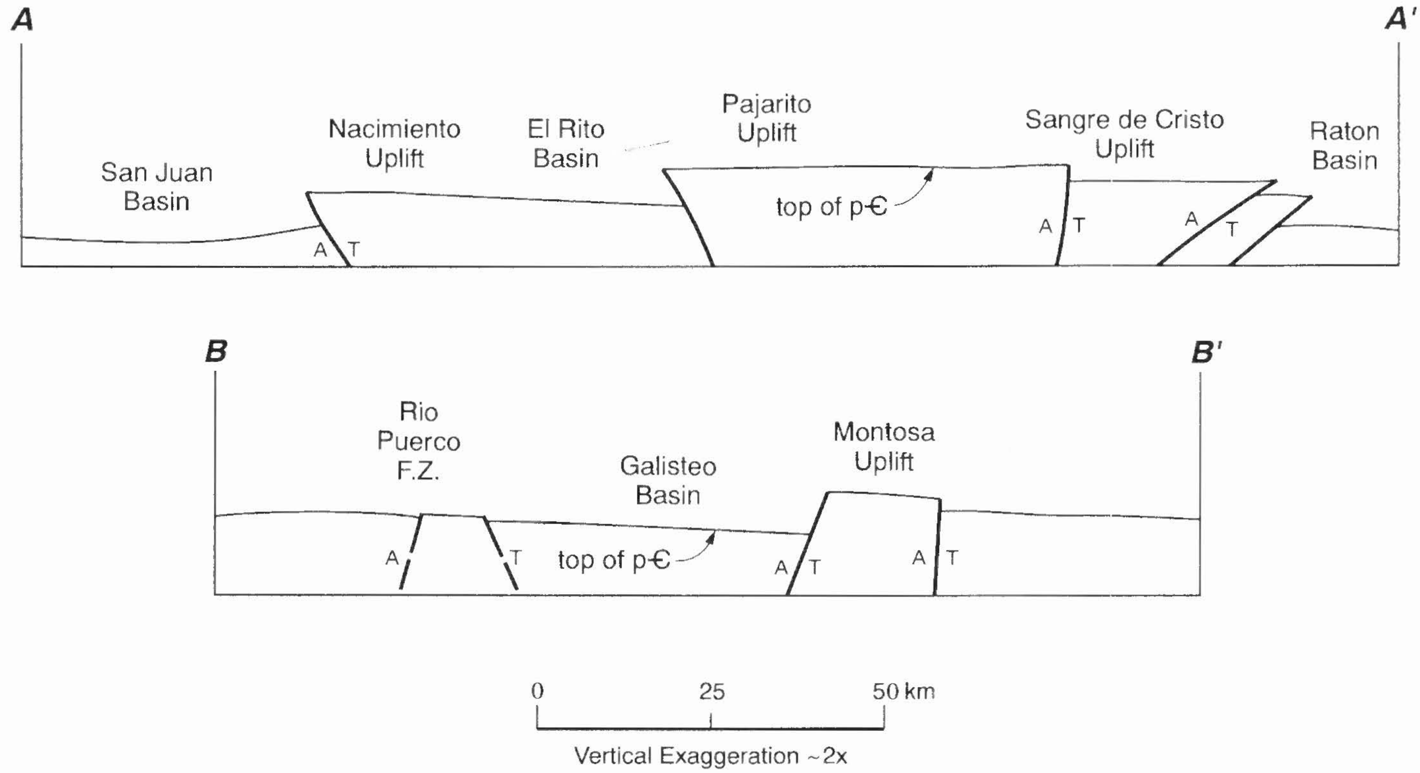

FIGURE 10. Schematic cross sections depicting contrasting structural styles across transpressional (A-A') and transtensional (B-B') parts of Laramide wrench-fault system in southern Rocky Mountains. Lines of section shown in Fig. 9.

during the Eocene (Chapin and Cather, 1981). This cross section somewhat resembles that of other transpressional structures (e.g., Lowell, 1972; Sylvester and Smith, 1976) but the width of the Laramide convergent wrench system in the southern Rocky Mountains far exceeds those documented in other areas. Cross section B-B', in contrast, depicts the proposed transtensional origin for the Galisteo basin. In cross section, the Galisteo basin resembles a southeast-tilted half-graben, although the bounding faults display evidence of normal strike-slip or oblique-normal slip. The extensional aspect of the Galisteo basin may explain the preservation of thick Paleogene and Mesozoic sequences within the northern Albuquerque Basin and the Hagen embayment. Due largely to the effects of tectonic inversion, such sequences appear to be absent within other basins of the central and northern Rio Grande rift, an observation that may be of considerable importance to petroleum exploration.

As shown by re-evaluated drill hole and geophysical constraints, Precambrian exposures on the Laramide Pajarito uplift extended at least 10 km west of Santa Fe and at least 20 km west of Tesuque in the central part of the Española half-graben. Sedimentologic data indicate Precambrian exposures were also extant along the western margin of the uplift, nearby to the north of St. Peter's Dome. It is entirely plausible that Precambrian rocks were exposed throughout other portions of Pajarito uplift, although testing of this hypothesis will require further borehole or geophysical data.

Stratigraphic and sedimentologic data indicate the Española half-graben has been tectonically inverted from the Laramide Pajarito uplift. Displacement reversal and down-to-the-east subsidence along the Pajarito fault zone was under way during Abiquiu deposition (late Oligocene–early Miocene). Continued subsidence and westward tilting of the Española half-graben resulted in deposition of about 3 km of the Santa Fe Group within the basin.

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