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PALEOGENE SYNOROGENIC SEDIMENTATION IN THE GALISTEO BASIN RELATED TO THE TIJERAS-CAÑONCITO FAULT SYSTEM

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Abstract—The strata between the Cretaceous Mesaverde Group and the Oligocene Espinaso Formation were deposited in a synorogenic, continental basin (the Galisteo basin) during the Laramide orogeny. Three lines of evidence suggest that the Tijeras-Cañoncito fault system controlled extensional subsidence of the Galisteo basin. First, stratigraphic thickening and highly variable paleocurrent directions adjacent to the fault system in both the Hagan and Cerrillos-Lamy areas indicate that the axis of the basin was parallel to the fault system. Second, there were large components of fault-parallel paleoflow in the lower unit of the basin adjacent to the fault system near Galisteo Creek. Paleoflow was both to the northeast and to the southwest, recording fault control on sediment dispersal. Third, the Tijeras-Cañoncito fault system is the only major fault system identified in the area, and is the most plausible structural control on Paleogene extensional subsidence. Although the fault system appears to have controlled a large part of the extensional subsidence of the basin, the fault system was not the southeastern boundary of the basin. The presence of Paleogene strata on the southeast fault block, the lack of scarp-derived deposits, and the scarcity of northwesterly paleoflow adjacent to the fault system preclude major uplift and denudation of the southeast fault block during the Laramide orogeny, and suggest that the fault system was located within the basin. Because the southeast block was not emergent, the maximum displacement magnitude of the Paleogene dip-slip component on the Tijeras-Cañoncito fault system is constrained to approximately the stratigraphic thickness of the strata of the Galisteo basin (about 1300 m, northwest-side-down).

INTRODUCTION

It has long been recognized that the strata of the Galisteo basin thicken substantially to the southeast, and this observation has been used repeatedly to suggest that the sediments were deposited in an actively subsiding basin during the Laramide orogeny (Stearns, 1943, 1953; Gorham, 1979; Gorham and Ingersoll, 1979; Ingersoll et al., 1990; Cather, 1992). Ingersoll et al. (1990) used the thickening to the southeast as evidence to suggest there was important structural control on subsidence, and they were the first to speculate that the Tijeras-Cañoncito fault system was the southeastern boundary of the Galisteo basin. Cather (1992) developed this hypothesis in a regional tectonic model wherein the Tijeras-Cañoncito fault system acted as a releasing bend in the right-lateral strike-slip system of the southern Rocky Mountains, and controlled extensional subsidence in a half-graben to the northwest of the fault system in the Paleogene. In this paper, we test this hypothesis by examining the sedimentology and paleocurrents of the strata of the Galisteo basin adjacent to the Tijeras-Cañoncito fault system.

THE TIJERAS-CAÑONCITO FAULT SYSTEM

The Tijeras-Cañoncito fault system comprises several northeast-trending, sub-vertical faults, including the Tijeras, Guiterrez, San Lazarus, Los Angeles and Lamy faults (Fig. 1). The fault system is regionally extensive; it has been mapped for more than 80 km from Kirtland Air Force Base on the southwest (about 16 km east of Albuquerque), to the Cañoncito area on the northeast (about 20 km south of Santa Fe). Following Lisenbee et al. (1979), Woodward (1984) and Maynard et al. (1990), we prefer the name "Tijeras-Cañoncito fault system" over "Tijeras fault zone" when referring to the entire structure. Both names are entrenched in the literature and are often used synonomously, but we recommend "Tijeras–Cañoncito fault system" because it approximately locates the structure, and also distinguishes it from the Tijeras fault, which is only part of the system.

The Tijeras-Cañoncito fault system has a history of recurrent movement. Slickensides on minor fault surfaces record strike-slip, dip-slip and oblique-slip motion (Abbott et al., in prep.). Lisenbee et al. (1979) suggested the fault system was active in the Precambrian and in the Pennsylvanian, but unequivocal evidence of such activity is lacking (Abbott et al., in prep.). The oldest documented activity is Laramide (80-40 Ma), supported by the results of this as well as other studies. En echelon folds (Chapin and Cather, 1981, p. 48) and fault slickensides (Abbott and Goodwin, this volume) in Mesozoic and Paleozoic rocks record right-lateral strike-slip motion. The Laramide orogeny is the only post-Mesozoic deformational event that is consistent with right-lateral motion on the Tijeras-Cañoncito fault system. Neogene activity is supported by strongly brecciated Oligocene rocks within the fault system in the Ortiz and San Pedro Mountains (Fig. 1; Maynard et al., 1990; Abbott and Goodwin, this volume), as well as slickensides that record left-lateral motion on the fault system. Faulted surficial deposits provide clear evidence for reactivation of the Tijeras fault in the Quaternary (Lisenbee et al., 1979; Abbott and Goodwin, this volume).

STRATIGRAPHY OF THE GALISTEO BASIN

Strata between the Upper Cretaceous Mesaverde Group (Holmes, 1877) and the Oligocene Espinaso Formation (Stearns, 1953) have traditionally been assigned to the Galisteo Formation (Hayden, 1869). These strata consist of fluvial mudstone, sandstone and conglomerate up to 1295 m thick (Gorham, 1979). Excellent lithologic descriptions of these strata are available for the Hagan Basin (Stearns, 1943; Harrison, 1949; Gorham, 1979), the Cerrillos-Lamy area (Stearns, 1943; Lucas, 1982), and the vicinity of St. Peter's Dome about 10 km south of Los Alamos (Cather, 1992). Measured sections were provided by Harrison (1949), Gorham (1979) and Lucas (1982). In a forthcoming paper (Lucas et al., in prep), it will be proposed that these strata should be subdivided into two formations. In light of imminent revision to the stratigraphic nomenclature, the term "Galisteo Formation" is abandoned in this paper. Herein we recognize two informal lithostratigraphic units. Based on close similarities in age, distribution and sedimentology, we consider both units to have been deposited in the Galisteo basin, and we refer to them collectively as the strata of the Galisteo basin. The lower unit unconformably overlies the Mesaverde Group. In the Cerrillos-Lamy area, the unconformity was mapped by Stearns (1953), Disbrow and Stoll (1957), Bachman (1975) and Johnson (1975). The lower unit consists of about 121 m of yellowish-brown and gray sandstone, mudstone, pebbly sandstone and minor conglomerate. In the Cerrillos-Lamy area, the lower unit is equivalent to units 10-21 of Lucas' (1982) measured section; in the Hagan Basin, the lower unit is the strata below the Lw-css member of Gorham (1979).

The upper lithostratigraphic unit unconformably overlies the lower unit. The contact is marked by a basal conglomerate that is ubiquitous in the Cerrillos-Lamy area. The basal conglomerate is 1-3 m of clast-supported pebble conglomerate. Clasts have a high degree of sphericity, and are composed of quartzite, gray limestone, chert and sandstone. Good exposures of the basal conglomerate are present in four localities: NE¼ sec. 19, T14N, R8E; SE¼SE¼ sec. 36, T15N, R9E; W½SE¼ sec. 16, T14N, R8E; and NW¼SW¼ sec. 6, T13N, R9E. The upper unit is a redbed sequence about 974 m thick of red mudstone, light gray sandstone

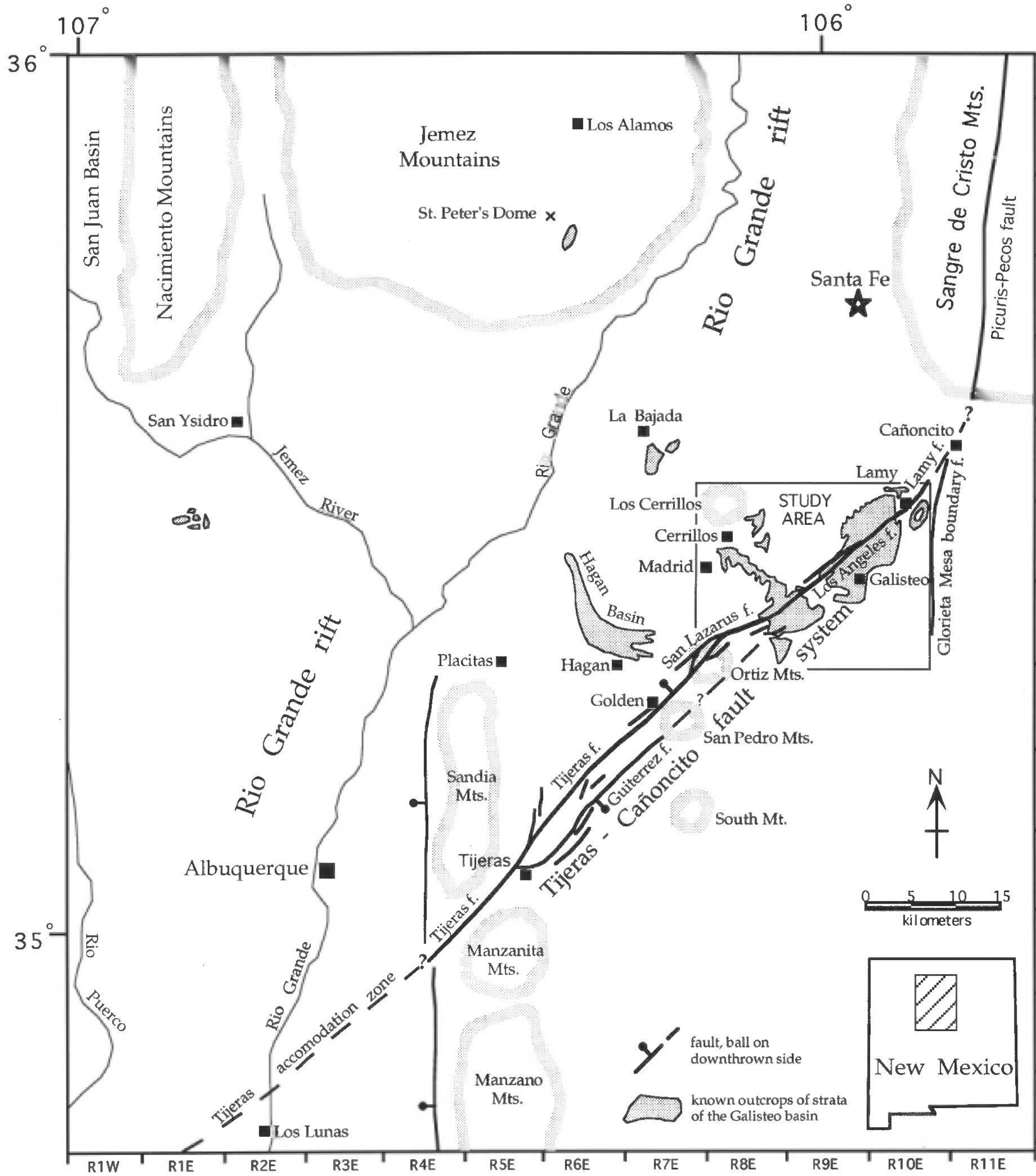

FIGURE 1. Location map of the Tijeras-Cañoncito fault system and known exposures of strata of the Galisteo basin.

and conglomerate. In the Cerrillos-Lamy area, the upper unit is equivalent to units 22-82 of Lucas' (1982) measured section; in the Hagan Basin, the upper unit is the strata above the Lb-ss, mdst member of Gorham (1979). Late Wasatchian through Duchesnean vertebrate fossils from this interval suggest that deposition of the upper unit spanned the entire Eocene (Lucas, 1982). The upper contact of the upper unit has been chosen in slightly different stratigraphic positions by different workers. Lucas (1982) provided a strong argument for locating it at the base of the lowermost major debris flow deposit or tuff of the overlying thick volcanic strata. This practice is accepted here.

STRATIGRAPHIC THICKNESS

Strata of the Galisteo basin thicken substantially to the southeast (Fig. 2). Stearns (1943) depicted an increase in stratigraphic thickness from about 350 m near La Bajada to about 1300 m near Lamy and Hagan. Gorham (1979) demonstrated that strata of the Galisteo basin thicken to the southeast in the Hagan Basin from 261 m to 1295 m. Both units contribute to the southeast thickening in the Hagan Basin; the lower unit thickens from 0 to 450 m, and the upper unit thickens from 261 to 850 m. This variation in thickness is not the result of post-Galisteo erosion, because deposition of the Espinaso Formation followed without interruption (Stearns, 1943). The variation in thickness is also not the result of onlap onto irregular topography. Though basal scours are present in both units, the local relief is small and limited to channels less than a few meters deep. There is no evidence for much local irregularity on either surface. One exception to the trend of southeastward thickening is the exposure near St. Peters Dome, where the strata of the Galisteo basin are over 630 m thick (Cather, 1992).

SPATIAL VARIATION IN LITHOLOGY

In the Cerrillos-Lamy area, there is no systematic relationship in either unit between lithology and geographic location. The exposures im-

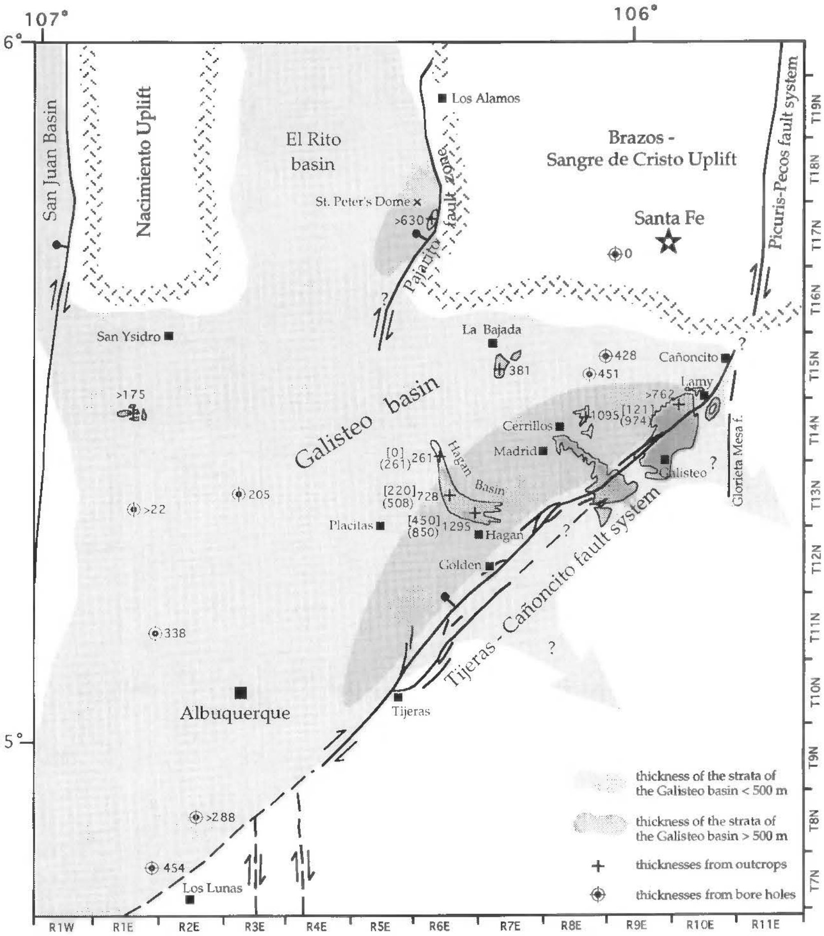

FIGURE 2. Thicknesses (in meters) of strata of the Galisteo basin. In addition to total thickness of undifferentiated strata of the Galisteo basin, thickness of the lower unit [brackets] and upper unit (parentheses) are locally indicated. Bore hole data is compiled from Lozinski (1988, 1994). Outcrop thicknesses are from Stearns (1943), Gorham (1979) and Cather (1992).

mediately adjacent to the Tijeras-Cañoncito fault system, for example, are similar in grain size and facies to exposures elsewhere in the Cerrillos-Lamy area. Though an outcrop in either unit generally consists of beds ranging in coarseness from conglomerate to mudstone, the relative abundances of conglomerate, sandstone and mudstone in an outcrop are similar throughout the Cerrillos-Lamy area (about 2/73/25 in the lower unit, and 5/40/55 in the upper unit). It is therefore not possible to delineate and contour areas in either unit within the Cerrillos-Lamy area based on overall coarseness. Similarly, it is not possible to contour the Cerrillos-Lamy area based on maximum clast sizes. Stearns (1943) noted that the largest clasts in the strata of the Galisteo basin in the Cerrillos-Lamy area are generally similar in size and composition to those in the Hagan Basin. The exposures near St. Peter's Dome are considerably coarser than in the Hagan Basin and the Cerrillos-Lamy area, and are clearly more proximal piedmont deposits (Cather, 1992).

PALEOCURRENTS

Treatment of data

Bedding in the Cerrillos-Lamy area has been tilted by subsequent deformation, so paleocurrent indicators must be restored to their original orientations. We assume that bedding was rotated about a single horizontal axis to its present orientation. The effect of tilting on the paleocurrent direction is removed, therefore, by restoring bedding to horizontal with one rotation about the line of strike.

Most paleocurrent measurements in the lower unit in the Cerrillos-Lamy area are of planar cross-stratification, although trough cross-stratification was also noted. The most abundant paleocurrent indicator in the upper unit is planar cross-stratification, though pebble imbrication, trough cross-stratification, and ripple cross-laminations are also locally present. Rose diagrams include all paleocurrent indicators in an area of exposure. Resultant vector means in each unit were calculated for high-order paleocurrent indicators (pebble imbrication and trough cross-stratification), for low-order paleocurrent indicators (planar cross-stratification and ripple cross-laminations), and for all paleocurrent indicators.

Several potential sources of paleocurrent variance are identified. A natural variation is inherent in the formation of paleocurrent indicators (Allen, 1967; Smith, 1972). Some paleocurrent variance arises from the procedure of rotating the paleocurrent indicator to its original depositional orientation. The assumption that bedding was rotated about a single horizontal axis is certainly not infallible, and the possibility of rotations about other axes has the potential to radically alter the restored paleocurrent direction. Finally, variance in paleocurrent rose diagrams may arise by grouping paleocurrents by geographic location, not stratigraphic position. Each paleocurrent rose diagram potentially reflects paleoflow of interfingering axial deposits and deposits that prograded transverse to the basin axis.

Lower unit

Paleocurrent directions in the lower unit are highly variable (Figs. 3, 4). Most of these paleocurrent indicators are planar cross-beds, though three measurements from exposures about 3 km east of Cerrillos are of trough cross-stratification that record paleoflow toward 308°, 330° and 341°. The mean vector of three measurements of trough cross-stratification (326°) is considerably different than the mean vector of five measurements of planar cross-stratification (133°). Paleocurrents are most variable adjacent to the Tijeras-Cañoncito fault system. Rose diagrams of paleocurrents from these areas are polymodal, recording significant paleoflow in all directions. The strongest components of paleoflow were

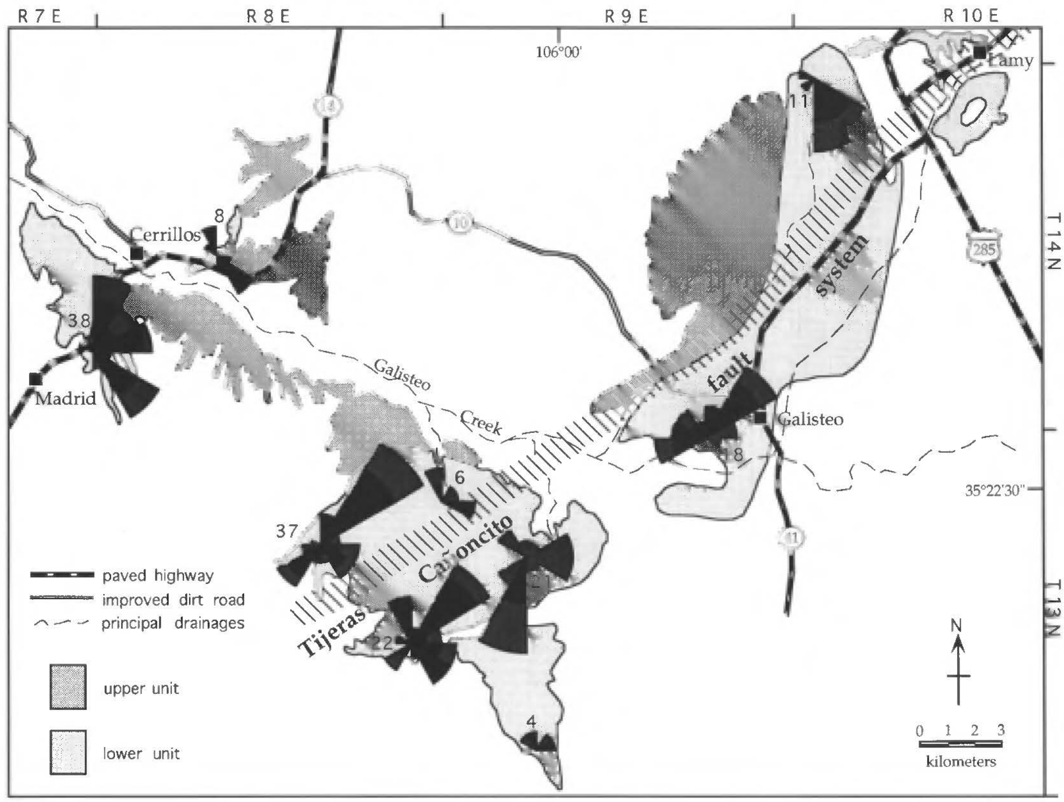

FIGURE 3. Paleocurrent rose diagrams of the lower unit in the Cerrillos-Lamy area. Rose diagrams are roughly scaled to represent the number of measurements. Black part of rose diagrams represents measurements where exposure afforded good three-dimensional control on the orientation of the paleocurrent indicator. Gray part of rose diagrams represents measurements from poorer exposure, where each measurement records only a component of the paleocurrent direction.

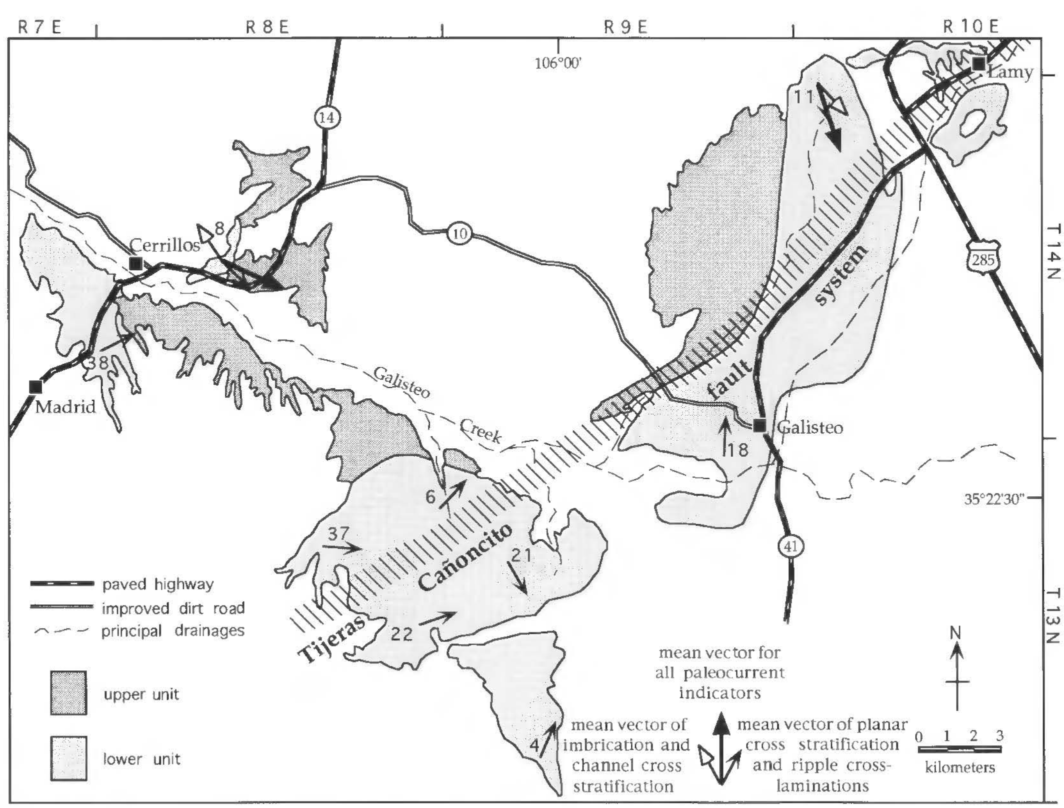

FIGURE 4. Resultant vector means of paleocurrents in the lower unit in the Cerrillos-Lamy area.

to the northeast and southwest, subparallel to the fault system. The same trends are evident at a larger scale (Fig. 5). In the Cerrillos-Lamy area, paleocurrent rose diagrams in the lower unit are polymodal, with large components of paleoflow sub-parallel to the fault system. In the Hagan Basin, paleoflow in the lower unit was dominantly to the south-southeast (Gorham, 1979).

Upper unit

Paleocurrent directions in the upper unit are also highly variable (Fig. 6). Paleocurrent indicators record considerable paleoflow in almost all directions. Despite high variability in individual paleocurrent directions, computed vector resultants are quite similar, with net paleoflow generally to the east and east-northeast (Fig. 7). A significant deviation from this trend is in exposures about 4 km west of the village of Galisteo, where paleocurrent indicators record westward paleoflow. Acknowledging the paucity of high-order paleocurrent indicators, there is general similarity between the mean vector resultants of high-order and low-order paleocurrent indicators. At a larger scale, paleocurrent directions in the Cerrillos-Madrid area are highly variable, but record a general eastward paleoflow (Fig. 8). Immediately adjacent to the Tijeras-Cañoncito fault system, paleoflow was more to the southeast. In the Hagan Basin, paleoflow was predominantly to the southeast and south (Gorham, 1979). A rose diagram of paleocurrents from the exposure near St. Peter's Dome is bimodal, with paleoflow to the south-southeast and northwest (Cather, 1992).

DISCUSSION AND CONCLUSIONS

Although there is clearly a progressive thickening of the strata of the Galisteo basin towards the Tijeras-Cañoncito fault system, thickness data alone do not preclude continuation of the basin southeast of the structure. The southeast side of the Tijeras-Cañoncito fault system is currently a structural high, so the thickness of strata removed by uplift and erosion subsequent to the Eocene is unknown.

The paleocurrents and sedimentology of the strata of the Galisteo basin provide additional insight into the development of the basin. Paleocurrent directions in both units are highly variable in the Cerrillos-Lamy area. Paleocurrent indicators from exposures of the upper unit on the southeast margin of the fault zone record paleotransport to the west, and paleocurrent indicators in the lower unit adjacent to the fault system record large components of paleotransport parallel to the fault system, both to the northeast and to the southwest. About 3 km east of Cerrillos, the computed vector resultants of high-order paleocurrents are roughly opposite that of low order paleocurrents. These observations are consistent with a basin axis in the Cerrillos-Lamy area. Bimodal and polymodal paleocurrent rose diagrams probably reflect paleoflow of interfingering axial deposits and deposits that prograded transverse to the basin axis. Geographic and stratigraphic variations in paleocurrents in the Hagan Basin suggest that the Hagan area also was near or within the basin axis (Gorham and Ingersoll, 1979). Thus, it appears that the basin axis paralleled the Tijeras-Cañoncito fault system.

Three lines of evidence suggest that the fault system was a control on subsidence and sediment dispersal. First, the axis of the basin was subparallel to the fault system. This is indicated by stratigraphic thickening adjacent to the fault system, and by highly variable paleocurrent directions adjacent to the fault system in both the Hagan and Cerrillos-Lamy areas. Second, there are large components of fault-parallel paleoflow in the lower unit in exposures adjacent to the fault system near Galisteo Creek. Paleoflow was both to the northeast and to the southwest, recording fault control on sediment dispersal. Third, the Tijeras-Cañoncito fault

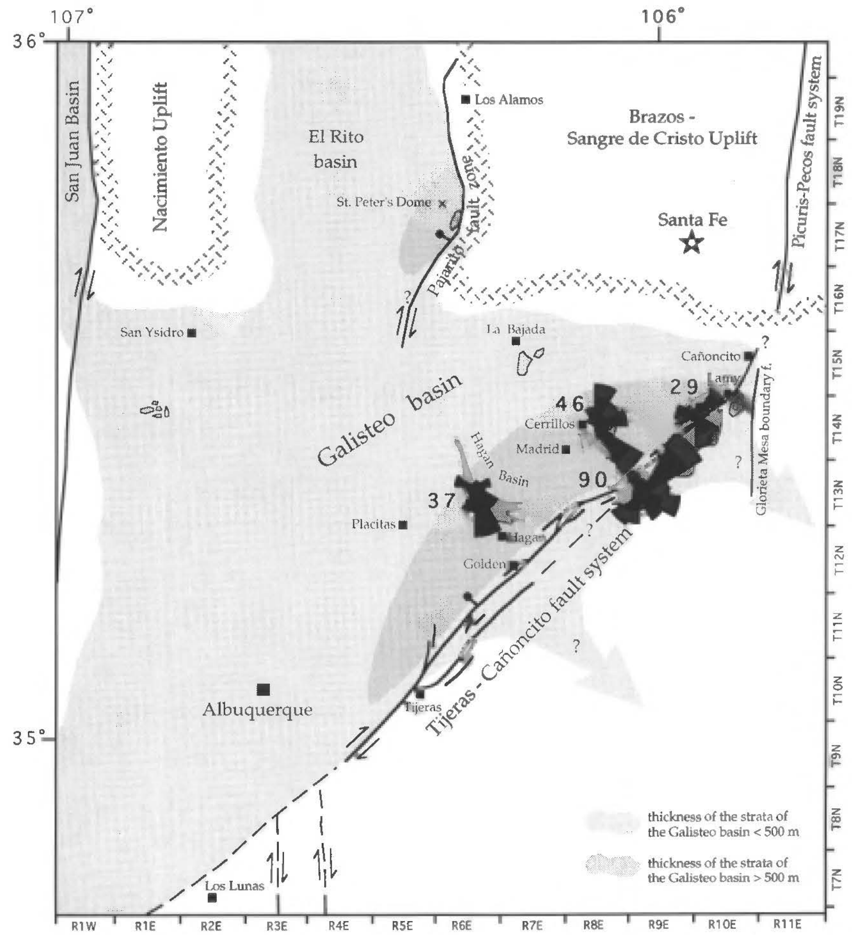

FIGURE 5. Synthesis of all paleocurrent data in the lower unit of the strata of the Galisteo basin. Data in the Hagan Basin are from Gorham (1979). See caption of Fig. 3 for explanation of rose diagrams.

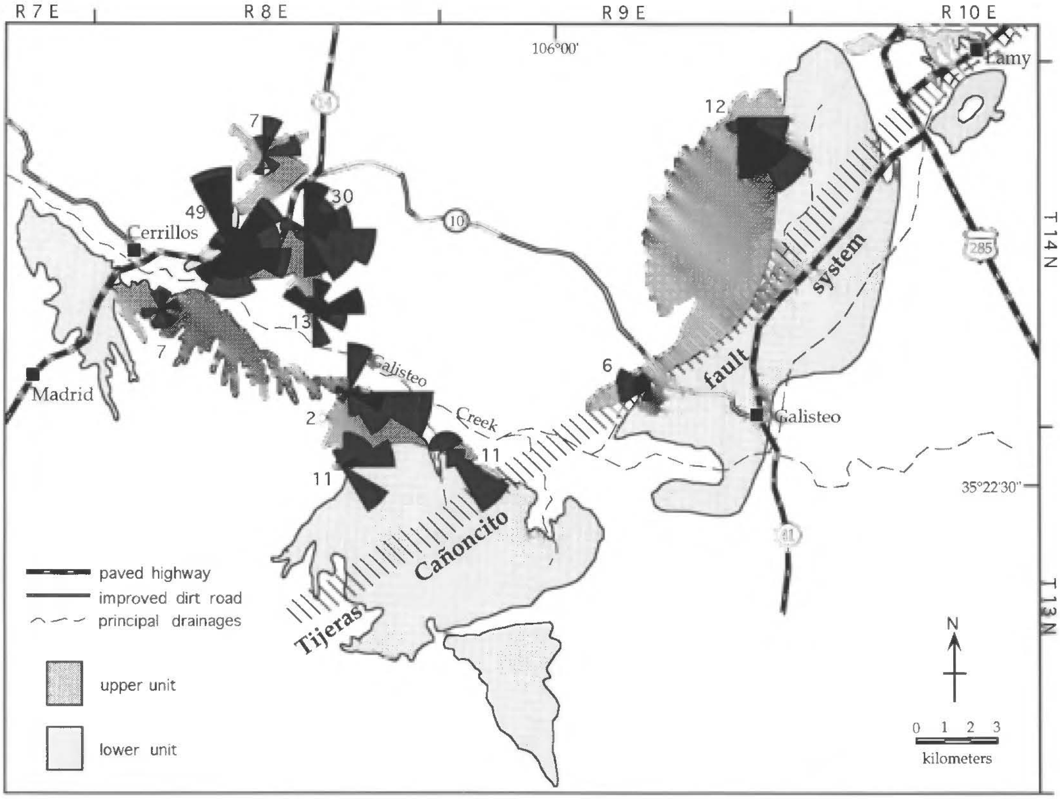

FIGURE 6. Paleocurrent rose diagrams of the upper unit in the Cerrillos-Lamy area. See caption of Fig. 3 for explanation of rose diagrams.

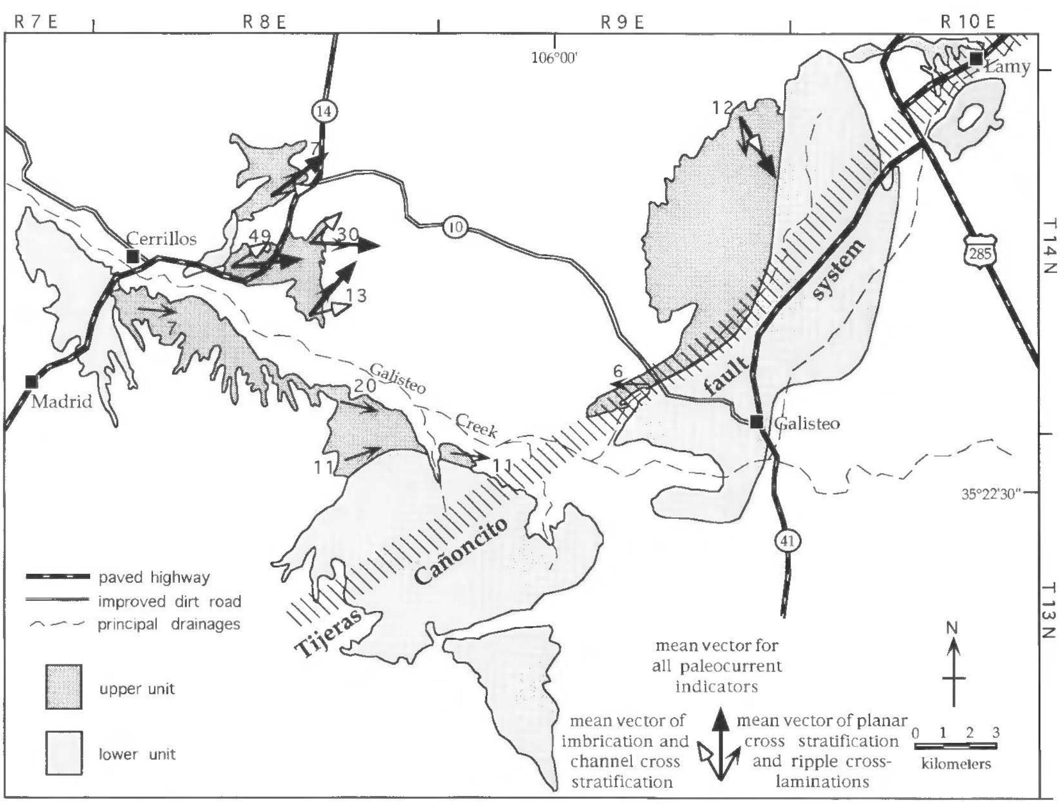

FIGURE 7. Resultant vector means of paleocurrents in the upper unit in the Cerrillos-Lamy area.

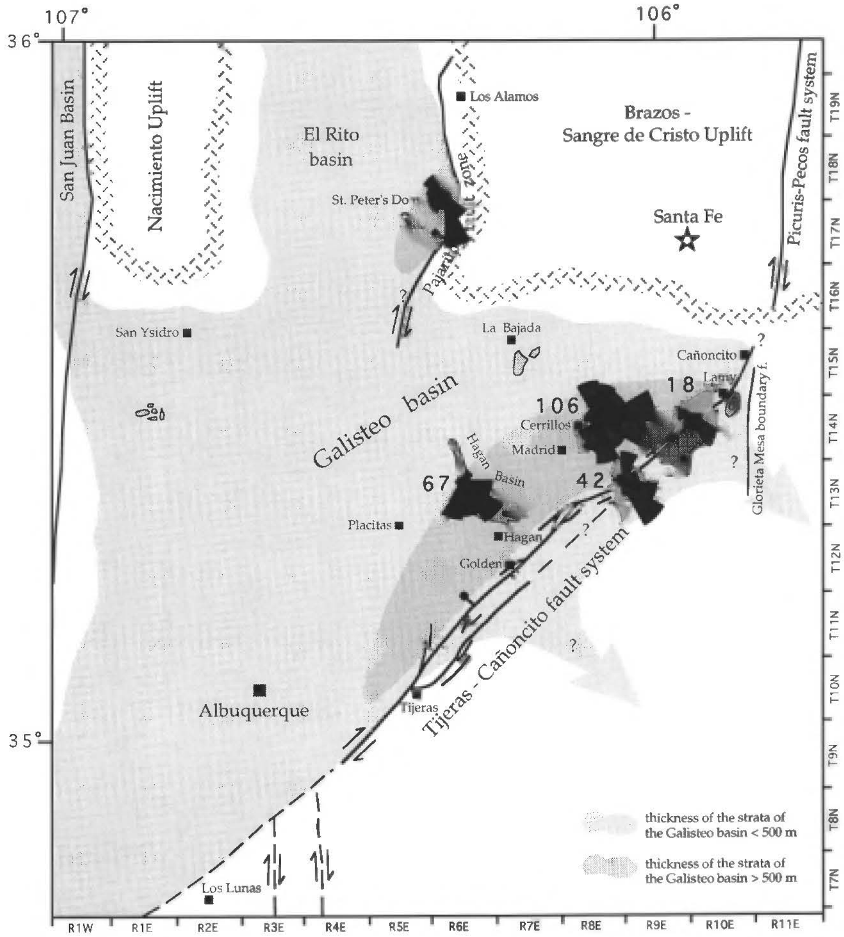

FIGURE 8. Synthesis of all paleocurrent data in the upper unit of the strata of the Galisteo basin. Data in the Hagan Basin are from Gorham (1979); data from exposures near St. Peter's Dome are from Cather (1992). See caption of Fig. 3 for explanation of rose diagrams.

system is the only major fault system identified in the area, and is the most plausible structural control on Paleogene extensional subsidence.

The southeast block of the Tijeras-Cañoncito fault system in the Laramide was not a major topographic high and significant source of sediment during deposition of the strata of the Galisteo basin. The lithologies in both units are similar throughout the Cerrillos-Lamy area. This demonstrates that coarse, proximal piedmont deposits did not prograde northwestward from the southeast fault block. Strata of the lower unit and Cretaceous strata currently exposed on the southeast fault block preclude major uplift and denudation of the southeast fault block during the Laramide orogeny. Although the fault system appears to have controlled a large part of the extensional subsidence of the basin, the fault system was not the southeastern boundary of the basin. The presence of Paleogene strata on the southeast fault block, the lack of scarp-derived deposits, and the scarcity of northwesterly paleoflow adjacent to the fault system suggest the fault system was within the basin.

Because the southeast block was not emergent, the maximum displacement magnitude of the Paleogene dip-slip component on the Tijeras-Cañoncito fault system is constrained to approximately the stratigraphic thickness of the strata of the Galisteo basin (~1300 m, northwest-side-down). This is a maximum estimate because the thickness of the strata of the Galisteo basin deposited on the southeast fault block is unknown. Though sedimentological study of strata of the Galisteo basin offers no constraints on the magnitude of horizontal displacement, the strike-slip component may have been substantial, as indicated by Laramide-age slickenside striations from other parts of the fault system that record a dominant component of strike-slip motion (Abbott and Goodwin, this volume; Abbott et al., in prep.). Structures indicative of right-lateral motion within the fault system and extensional subsidence of the Galisteo basin to the northwest lend support to Cather's (1992) hypothesis that the Tijeras-Cañoncito fault system accommodated right-lateral transtensional motion in the Paleogene.

In summary, stratigraphic thickening and highly variable paleocurrent directions in the strata of the Galisteo basin adjacent to the Tijeras-Cañoncito fault system suggest the fault system was a significant control on basin subsidence and sedimentation. The presence of Paleogene strata on the southeast fault block, the scarcity of northwest paleoflow, and the lack of scarp-derived deposits indicate that the Tijeras-Cañoncito fault system was not the southeastern boundary of the Galisteo basin. The fault system appears to have operated within the basin. Because the southeast block was not emergent, the maximum displacement magnitude of the Paleogene dip-slip component on the Tijeras-Cañoncito fault system is constrained to approximately the stratigraphic thickness of the strata of the Galisteo basin (~1300 m, northwest-side-down).

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