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ABSTRACT

Paleomagnetic data from parts of the northern Rio Grande rift provide evidence for clockwise (CW) and counterclockwise (CCW) vertical-axis block rotations associated with strike-slip deformation along basin-bounding faults during rift evolution. Despite the spatial consistency of the results, the quality and statistical significance of data sets are difficult to evaluate because of small sample size and potential failure to average secular variation. To understand the extent, importance, and origin of such rotations, we report paleomagnetic data from Tertiary intrusive and volcaniclastic rocks in the Cerrillos Hills and surrounding areas in the Española Basin. Paleomagnetic data from in situ Tertiary intrusions and tilt-corrected volcaniclastic strata of the Oligocene Espinaso Formation sampled at four localities yield a grand mean of declination = 342.9° and inclination = 58.3° ($\alpha$95 = 3.5°; $N = 32$ sites of normal polarity/21 reverse). Correction for minor postemplacement tilt of the Cerrillos Hills and La Cienega data sets yields a grand mean (declination = 349.5°, inclination = 55.3°, $\alpha$95 = 3.4°) that is indistinguishable from the 30 Ma reference direction for the study area, and there is no evidence of rotation (R = 1.8° ± 6.4°). However, if an alternative reference direction is used, minor CCW rotation (–6.6° ± 5.8°) is possible. Our data suggest that the magnitude of rotation in the Española Basin is significantly less than previously estimated and may be negligible. Regardless, paleomagnetic data from elsewhere in the basin suggest that CCW rotations may be an important component of recent rift extension and deformation.

INTRODUCTION

The Rio Grande rift is a major intracratonic rift that separates the thick and relatively undeformed crust of the Colorado Plateau on the west from the Great Plains of the stable craton to the east (Kelley, 1977; Chapin and Cather, 1994). It extends from near the vicinity of Leadville, Colorado, southward to where it merges with the eastern Basin and Range Province of eastern Arizona, New Mexico, and northern Mexico (Fig. 1A). It is characterized by high heat flow, recent crustal deformation, and Cenozoic to Holocene mafic magmatism. The amount of extension increases southward, and the relative elevation of fault-bounded basins decreases. In northern New Mexico, the structural manifestation of the rift is a series of right-stepping, asymmetric fault-bounded en echelon basins (Kelley, 1982). From south to north, these are the Albuquerque, Española, and San Luis Basins, respectively (Fig. 1A). Rift deformation from ca. 30 Ma to ca. 20 Ma was characterized by a broad zone of distributed extension along low-angle faults, crustal doming, deposition of sediments, and widespread magmatic activity (Chapin, 1988; Prodehl and Lipman, 1989). Formation of growth structures in sedimentary basin fill indicates that extension and deposition were coeval (Minor et al., 2006). Deformation during this period may have resulted from mantle asthenospheric upwelling and thermal lithosphere erosion (Seager and Morgan, 1979; Morgan et al., 1986; Olsen et al., 1987; Wilson et al., 2005). Between ca. 20 and 10 Ma, the rate of extension accelerated, but rifting was restricted to a narrower zone and characterized by high-angle normal faulting and the onset of alkalic mafic magmatism (Golombek et al., 1983; Prodehl and Lipman, 1989; Baldridge et al., 1991). The change in structural style has been inferred to reflect a major change in the regional stress field in response to a change in North American–Pacific plate boundary conditions (Golombek et al., 1983; Prodehl and Lipman, 1989; Atwater and Stock, 1998).

Paleomagnetism can be a powerful tool in identifying and understanding the mechanisms of distributed crustal deformation in orogenic belts and extensional settings (House, 1989; Beck, 1989) such as the Rio Grande rift. The paleomagnetic method is well suited to identifying crustal block rotations where the remanent magnetization of a series of rocks, acquired during a sufficiently long interval (i.e., generally 10° to 10°) in order to sufficiently average the effects of paleosecular variation, can be compared with time-equivalent reference directions from undeformed rocks (typically based on paleomagnetic poles derived from rocks of the stable craton) to identify the sense and magnitude of rotations. With adequate sampling, the size and geometry of rotational domains may be identified. Such studies provide important insight into mechanisms responsible for crustal rotations in contractional orogenic belts, as well as extensional and transtensional/transpressional regimes.

In northern New Mexico, several paleomagnetic studies (Brown and Golombek, 1985; Brown and Golombek, 1986; Salyards...
et al., 1994) have reported data supporting the presence of statistically significant vertical-axis block rotations associated with extension accompanying development of the Rio Grande rift. In particular, paleomagnetic studies of intrusive rocks of the Ortiz porphyry belt within the Española Basin (Fig. 1B) yielded an apparent counterclockwise (CCW) rotation of \(-17.8^\circ \pm 11.4^\circ\) (Brown and Golombek, 1986). The CCW rotations were postulated to result from left-lateral slip along major faults bounding the rift (Muehlberger, 1979; Brown and Golombek, 1986) (Fig. 1B). Outside of the Española Basin, other studies have shown either negligible or statistically significant clockwise (CW) rotations, thus documenting a complex image of crustal block rotation accompanying rift extension. Many paleomagnetic rotation estimates from the rift and surrounding areas are based on small sample populations, and it is unclear whether results from individual studies adequately sampled paleosecular variation. Hence, it is possible that some reported rotations could be artifacts of small sample size or may arise from other complications within individual data sets. The purpose of this study is to better assess possible block rotations in the southern Española Basin and thus contribute to a better understanding of the kinematics of Rio Grande rift formation. Accordingly, we conducted a paleomagnetic study of intrusive and volcaniclastic rocks within the Cerrillos Hills and surrounding areas of the Española Basin (Figs. 1B and 2).

Figure 1. Tectonic map of part of northern New Mexico showing the location of the Cerrillos Hills and the Española block. Circles show the location of paleomagnetic sites sampled in this study. T-CF—Tijeras-Cañoncito fault zone; PFZ—Pajarito fault zone; EF—Embudo fault zone; P-PF—Picuris-Pecos fault zone; LBF—Lobato Mesa fault; SFF—San Felipe fault; SF—Sandia fault; ABQ—city of Albuquerque. Location map modified from http://cires.colorado.edu/science/groups/sheehan/projects/riogrande/images/faq2.jpg. Faults on tectonic map are from the U.S. Geological Survey Quaternary fault and fold database (http://gldims.cr.usgs.gov); geologic units are from Green and Jones (1997).
Paleomagnetic studies documenting the apparent CW and CCW tectonic rotations in the northern Rio Grande rift have been conducted by Brown and Golombek (1985, 1986), Salyards et al. (1994), and Minor et al. (2006). In addition, paleomagnetic data presented in other studies of a nontectonic nature, but used to argue for presence or absence of rotations by Brown and Golombek (1985, 1986), include those by Doell et al. (1968), MacFadden (1977), and Barghoorn (1981). These studies, as well as more recent contributions applicable to identification of crustal rotations in the Española Basin, are described here.

In assessing the results of these and comparable studies, it is important to recognize that estimates of the magnitude of apparent rotation cited in individual studies are critically dependent on the choice of expected directions, which are obtained from reference paleomagnetic poles assuming the fundamental axial geocentric dipole hypothesis. The rotation estimates for most studies described here were based on comparisons with expected directions calculated by Brown and Golombek (1985, 1986) using a subset of poles averaged from the compilation of Irving and Irving (1982). Reference poles based on other North American data sets (e.g., Harrison and Lindh, 1982; Diehl et al., 1988) yield similar expected directions, with variable degrees of precision. Recently, Besse and Courtillot (2002) combined selected high-quality paleomagnetic data from the major continents and kinematic plate motion models to produce a master and “synthetic” apparent polar wander (APW) path based on a very large, global data set in an effort to improve the robustness of APW paths for each continent. The synthetic APW path utilizes new paleomagnetic results from the Global Paleomagnetic Database (GPMD) (June 1999 V3.3) of McElhinny and Lock (1995) determined during the past 25 a in addition to those used by earlier studies, has improved data selection criteria, and is based on a 10 Ma sliding window. In general, this approach should result in reference directions of specific time periods in the Tertiary that are more reliable than those used by earlier studies. We note that in this compilation, only two of the five poles utilized by Irving and Irving (1982) for the 24–36 Ma time period have been found to be acceptable. In Table 1, we list Tertiary and Holocene paleomagnetic poles and their corresponding expected directions relevant to the studies described herein.

We note that the expected reference directions for the study coordinates (35.5°N, 106°W) from the Brown and Golombek (1986) 24–36 Ma and the 30 Ma synthetic poles of Besse and Courtillot (2002) differ by 7.5° ± 4.1°. Because the Besse and Courtillot (2002) expected direction is located west of that used by Brown and Golombek (1986), it will thus yield estimates of the magnitude of apparent rotation that differ from previously estimated values; in the case of CCW rotations, the estimates will be more conservative. Table 2 presents summary paleomagnetic results from these studies, apparent rotation statistics, and the poles used in the calculation of those estimates. In most cases, these estimates are based on statistics provided by the cited sources; in others, they are based on our calculation or recalculation from their data with rotation estimates based on the expected direction derived from the Besse and Courtillot (2002) 30 Ma pole. Because of the angular difference between expected directions, the results from the original reports and our recalculated rotation estimates are not directly comparable. For recalculations of paleomagnetic data from Paleocene-Pliocene rocks, expected directions and rotation estimates were based on the hypothesis of a modern-day axial geocentric dipole. Paleomagnetic results from sedimentary rocks are described first, followed by results obtained from volcanic and intrusive rocks.

### Studies of Sedimentary Rocks

Several paleomagnetic studies have targeted basin-fill sedimentary rocks exposed within the Española Basin and surrounding areas, including both the Laramide (middle Eocene) Galisteo Formation and middle Miocene to early Pliocene rocks of the Santa Fe Group within the Española Basin. Barghoorn (1981) studied the stratigraphically lowest unit, the middle to late Miocene Nambé, Skull Ridge, and Pojaque members of the Tesuque Formation, north of Santa Fe, and MacFadden (1977) studied the upper unit of the Santa Fe Group, the late Miocene–early Pliocene Chamita Formation, north of Española, New Mexico, along the southwestern boundary of the Española block. Paleomagnetic analysis of the Tesuque Formation yielded a well-defined magnetostatigraphic sequence. Despite being nearly antipodal, the means of the normal and reverse polarity magnetizations are distinct at the 95% confidence level; this difference was attributed to incomplete removal of a Brunhes chron normal polarity remanence during demagnetization for many reverse polarity samples. The mean direction, based on only normal polarity magnetizations, is declination (D) = 338.8° and inclination (I) = 48.7° (S. Barghoorn, 1982, personal commun. in Brown and Golombek, 1986), which yields a statistically significant apparent CCW rotation of –18.5° ± 5.8° when compared to the reference direction based on their compilation of the <10 Ma poles from Irving and Irving (1982) (Table 2). Because the result is based solely on the normal polarity data, and the number of samples is low, it may not fully average paleoscalar variation.

Paleomagnetic studies from the Chamita Formation included fluvial mudstones and sandstones, which represent some of the youngest sediments deposited in the rift. The samples were subjected to alternating field demagnetization
and yielded antipodal normal and reverse polarity magnetizations with a group mean direction, based on 111 samples, of \( D = 345.8^\circ, I = 48.8^\circ \) (\( k = 19.7, \alpha^95 = 3.1^\circ \)). As noted by MacFadden (1977) and Brown and Golombek (1985), this direction is discordant with respect to their <10 Ma reference pole, yielding a statistically significant apparent CCW rotation of \(-11.5^\circ \pm 5.3^\circ\) (Table 2).

Salyards et al. (1994) collected samples from five broadly distributed localities within the Española Basin in fine-grained sedimentary rocks of the Tesuque Formation north of Santa Fe. All samples were subjected to detailed alternating field and thermal demagnetization, and characteristic remanent magnetization directions were determined using principal components analysis (Kirschvink, 1980). Paleomagnetic and rock magnetic behaviors indicate that the main magnetization carrier in the Tesuque Formation samples is magnetite with minor hematite. Some samples showed evidence of significant chemical remagnetization, and the five localities have accepted-to-rejected sample ratios between 43% and 79%. Despite the fact that the sampling strategy was designed to adequately average paleosecular variation, four localities were dominated by samples of either normal or reverse polarity, and only one locality had a sufficiently robust mixture of normal and reverse polarity samples. The five locations yielded group-mean directions with tilt-corrected declinations (after inversion of reverse polarity data to normal polarity) ranging from 330.2° to 355.5° and inclinations from 36.7° to 55.4°. The mean directions indicate apparent CCW rotations of 5° to 12° (Table 2) based on comparison with expected directions calculated from an interpolation of the 20 Ma pole of Harrison and Lindh (1982). The locality with the largest apparent discordance (SFCA) is also the one with the lowest percentage of acceptable samples (10 acceptable samples of 23, all of a single polarity) and the largest \( \alpha^95 \) value (12.7°). The low sample number and presence of only a single polarity make several of these localities questionable as to whether they may have fully averaged paleosecular variation; rotation estimates derived from these localities must therefore be used with caution. Salyards et al. (1994) interpreted their data to indicate that the magnitude of apparent tectonic rotations within the Española block varies significantly, ranging from essentially zero on the east side to larger values on the west side. Furthermore, they argued that three of four localities in the western part of the rift block experienced rotation about nonvertical axes.

In the Hagan and Española Basins, Prothero and Lucas (1996) conducted magnetostratigraphic studies of fluvial sandstones and mudstones of the middle Eocene Galisteo Formation. Two localities were studied, one in Arroyo del Tuerto in the Hagan Basin, southwest of Madrid, and the other east of Cerrillos. Samples were subjected to alternating field and thermal demagnetization. The Cerrillos area samples yielded magnetizations of normal and reverse polarity and a modified positive fold test. Similar results were obtained from sedimentary rocks at Arroyo del Tuerto. The mean directions reported by Prothero and Lucas (1996) appear rotated in a CCW sense. Unfortunately, critical components of the analysis, including numbers of samples used to define mean directions, the ways in which mean directions were obtained, etc., were not reported. Overall, the number of independent readings of the field appears small.
and reported \( \alpha_{95} \) values are large (i.e., \( \alpha_{95} \) values range from 13° to 19°). Given the lack of detail and summary data provided by the authors, this data set, although potentially of value, cannot be used to assess the sense and magnitude of rotations, and their data are not included in Table 2.

### Studies of Igneous Rocks

The earliest paleomagnetic study of volcanic rocks in northern New Mexico involved the ca. 1.6–1.2 Ma Bandelier Tuff cooling units and younger, postcaldera eruption rhyolites of the Jemez Mountains by Doell et al. (1968) as part of their contributions to the development of the geomagnetic polarity time scale. They documented a normal-reversed-normal polarity sequence showing the transition between the Matuyama and Brunhes polarity chron and identified the presence of the Jaramillo subchron within the reverse polarity Matuyama chron (now known to be a distinctly different polarity event called the Santa Rosa event; Singer and Brown, 2002). Individual samples were subjected to alternating field or thermal demagnetization, and site-mean directions were determined by the peak demagnetizing field that minimized dispersion based on the precision parameter \( k \). Incorporating paleomagnetic data reported by Doell et al. (1968), Brown and Golombek (1985) calculated a mean direction for volcanic rocks west of the Española Basin of \( D = 5.3°, I = 51.2° (k = 44.4, \alpha_{95} = 5.8°, N = 15 \) sites). The mean direction provides an apparent CW rotation estimate of 8.0° ± 9.2° with respect to the their <10 Ma reference direction based on poles from Irving and Irving (1982) (Table 1). Paleomagnetic data from the Bandelier Tuff and younger rhyolites have been augmented by studies by MacDonald and Palmer (1990) and Singer and Brown (2002). Using paleomagnetic data reported by those studies combined with data from Doell et al. (1968), and eliminating transitional field directions, 15 independent readings of the geomagnetic field from 45 sites show a mean of \( D = 5.3°, I = 51.3° (k = 48.2, \alpha_{95} = 5.6°) \), which is indistinguishable from the mean direction reported by Brown and Golombek (1985). However, our comparison of this mean direction with the expected direction based on the geocentric axial dipole hypothesis (GAD) yields a statistically insignificant CW rotation estimate of 5.3° ± 7.1° (Table 2).

Paleomagnetic data from volcanic rocks of the Lobato Basalt, Tschicoma Formation, Paliza Canyon Formation, Santa Fe basalts, and Cerros del Rio volcanics were reported by Brown and Golombek (1985). These flows range in age from Miocene to Pliocene-Pleistocene and are exposed at locations both within and north of the Española Basin. Samples were subjected to progressive alternating field demagnetization. Four sites from ca. 10 Ma Santa Fe basalts from near Chili, New Mexico, yielded well-defined means at the site level but poorly defined group mean directions in either in situ or tilt-corrected coordinates (\( \alpha_{95} \) values of 22° and 39°, respectively). The 8.9–9.1 Ma Paliza Canyon Formation yielded sites with both normal and reverse polarities, with a group mean of \( D = 9.2°, I = 51.1° (k = 29, \alpha_{95} = 11.3°, N = 7 \) flows), yielding a statistically insignificant apparent CW rotation of 11.9° ± 17.4°. Seven sites in flows from the 7.5 Ma Lobato Basalt from the northeastern part of the Jemez Mountains along the western part of the Española Basin yielded a group-mean of \( D = 4.5°, I = 51.8° (k = 21, \alpha_{95} = 13.5°) \); this result yields a statistically insignificant rotation of 7.2° ± 14.3°. Fifteen sites in 6.7–3.7 Ma quartz latites of the Tschicoma Formation were collected in the central and northern parts of the Jemez Mountains. These yielded 13 acceptable sites, with eight of normal polarity, four of reverse polarity, and one with an intermediate field direction. Based on 12 sites, a group mean of \( D = 16.7°, I = 50.0° (k = 21, \alpha_{95} = 9.7°) \) was obtained. Twenty sites were collected from flows of the Pliocene–Pleistocene Cerros del Rio volcanics southeast of the Jemez Mountains, along the southern margin of the Española Basin. These rocks yielded normal and reverse polarity sites with unusually high dispersion. The 12 sites considered acceptable yielded a mean direction of \( D = 340.2°, I = 53.6° (k = 10, \alpha_{95} = 14.4°) \) (Cerros del Rio volcanics 1, Table 2), with a statistically insignificant CCW rotation of −17.1° ± 20.5°. This estimate must be used with caution, however, because the data table shown in Brown and Golombek (1985) includes a site direction that is a transitional field direction (site 68, \( D = 14.2°, I = 12.6°, \alpha_{95} = 23.9° \)) and should not have been included in the calculation of the group mean direction, and several sites have large \( \alpha_{95} \) values (>15°) or widely dispersed directions. Using only five well-grouped site-mean directions, we obtain a revised mean of \( D = 340.8°, I = 61.9° (k = 74.9, \alpha_{95} = 8.9°) \). Although essentially identical to the Cerros del Rio mean reported by Brown and Golombek (1985), it is considerably better defined and yields a statistically significant CCW rotation of −19.2° ± 14.8° based on the expected direction for the study derived from the GAD (Cerros del Rio volcanics 1 recalculated, Table 2). The low number of reliable independent observations renders this result problematic in terms of adequately assessing the magnitude of potential tectonic rotation. Similar problems exist with several of the results summarized here.

New paleomagnetic results from the Pliocene Cerros del Rio volcanic field were recently reported by Thompson et al. (2006). These data included dual polarity directions from 22 sites distributed throughout the volcanic field, although a mean direction was not calculated. They noted that their results were complicated by the effects of lightning strikes (also noted by Brown and Golombek, 1985), as several sites have high natural remanent magnetization intensities and high within-site dispersion. Excluding sites with \( \alpha_{95} \) values >15° and unusually shallow or unusual directions, we obtain a mean direction based on 18 sites of \( D = 345.3°, I = 52.5° (k = 22.4, \alpha_{95} = 7.5°) \). A comparison of this with the expected direction based on GAD yields a statistically significant apparent CCW rotation of −14.7° ± 9.8° and \( F = 2.5° ± 5.9° \) (Cerros del Rio volcanics 2, Table 2).

The oldest igneous rocks used to evaluate tectonic rotations in the Española Basin are the mid-Tertiary intrusive and extrusive rocks of the Ortiz porphyry belt. Brown and Golombek (1986) reported data from 15 sites in volcanic and intrusive rocks distributed over a broad area of the basin, with six from the Ortiz Mountains south of Madrid, three from the Cerrillos Hills, north of Cerrillos, one site located northwest of La Cienega, and three from north of Cienega. One site was also collected in the Hagan embayment. The samples were subjected to stepwise alternating field and thermal demagnetization. An undocumented number of sites in dikes proved to be paleomagnetically unstable during laboratory measurement and were abandoned as accurate paleomagnetic recorders. Following demagnetization, 13 sites yielded well-behaved samples with site-mean directions that were generally well grouped (\( \alpha_{95} \) values from 4.6° to 24.1°) and similar to those expected for rocks of mid-Tertiary age. Nine sites were of normal polarity, the rest were reverse. After inversion of reverse polarity sites, these sites yielded a combined mean of \( D = 337.8°, I = 42.1° (k = 17.0, \alpha_{95} = 10.3°) \). The 13 site-mean directions show a northeast-southwest streaking far in excess of that expected from a standard Fisherian distribution. They compared their group mean to an expected direction derived from the 30 Ma reference pole of Irving and Irving (1982) and reported an apparent, statistically significant CCW rotation of −17.8° ± 11.4° and apparent flattening of ~10° (Table 2), although the flattening is not statistically significant.

### GEOLOGIC SETTING

The Española crustal block, which contains the Española Basin, is a large (50 km wide by 150 km long) diamond-shaped region bounded...
by the Tijeras-Cañoncito fault zone to the south, the Pecos-Picuris fault zone to the east, the Embudo fault zone to the north, and the Pajarito fault zone and other faults to the west (Fig. 1B) (Kelley, 1978; Muchlberger, 1979; Brown and Golombek, 1986). The Tijeras-Cañoncito and Embudo fault zones are major fault zones that separate domains of differential crustal extension with opposing tecton domains characterized by east-dipping synrift strata in the San Luis and Albuquerque Basins and west-dipping synrift strata in the Española Basin (Chapin and Seager, 1975; Kelley, 1982; Golombek et al., 1983; Chapin, 1988; Thompson et al., 2006). Several faults that bound the Española block show evidence of complicated fault history, including recent strike-slip movement. For example, the Tijeras-Cañoncito fault, a northeast-trending zone of faults that extends from the Albuquerque Basin to ~20 km south of Santa Fe, where it links up with the Picuris-Pecos fault, has a history of displacement and reactivation from the Proterozoic to Holocene (Lisenbee et al., 1979; Abbot et al., 2004). The fault was clearly active during Late Cretaceous–early Tertiary Laramide shortening, and was reactivated during the transition between Laramide shortening and Oligocene and younger rift extension. The fault zone may have controlled emplacement of Tertiary intrusions and associated mineralization (Woodward, 1984). Although the predominant Cenozoic movement on this fault has been dip slip, structures associated with the Tijeras-Cañoncito fault system record episodes of both right-lateral and left-lateral moment. Left-lateral strike-slip movement on this fault has continued into the Quaternary (Abbot et al., 2004). To the north, the northeast-striking Embudo fault zone separates uplifted Precambrian rocks of the Picuris Mountains from Cenozoic basin fill of the San Luis Basin. The fault shows a complicated history of normal, reverse, and strike-slip displacement on microfaults in Santa Fe Group sedimentary rocks and folded Miocene-Pliocene basaltic of the Taos Plateau volcanic field (Muehlberger, 1979; Dungan et al., 1984). Near Pilar, New Mexico, Steinplass (1981) documented evidence of left-lateral movement on the Embudo fault based on slickensides, fault drag, and fault displacement. He considered this displacement to be largely Pliocene in age. North-trending faults of the Picuris-Pecos and Pajarito and related fault zones show evidence of complicated fault histories, but recent strike-slip displacement has not been documented, although the fault geometry appears to be consistent with left slip as suggested by Brown and Golombek (1986). Detailed discussions regarding the displacement histories of fault zones that bound the Española block are provided by Lisenbee et al. (1979), Muchlberger (1979), Brown and Golombek (1986), and Abbot et al. (2004).

Middle Tertiary intrusions in and adjacent to the Española block are exposed in a generally north-northeast–trending 40-km-wide zone of Oligocene rocks, laccoliths, dikes, and sills of the San Pedro–Ortiz porphyry belt (Figs. 1B and 2), which intrude Paleozoic to early Tertiary sedimentary strata (Maynard, 2005). Geologic mapping and published data have defined 12 distinct laccolith and batholithtic centers (Woodward and Ingersoll, 1979; Maynard et al., 1991; Maynard, 1995). The igneous rocks consist of two petrographic suites: early calc-alkaline laticies and quartz laticies emplaced between ca. 36 and 34 Ma; and alkaline laticites and coeval gold-mineralized monzonites between ca. 31 and 28 Ma (Bachman and Mehnert, 1978; Baldridge et al., 1980; Kautz et al., 1981; Kay, 1986; Maynard et al., 1990; Sauer, 1999; Abbot et al., 2004; Maynard, 2005). Within the basin, however, dikes as young as 26.55 Ma (i.e., the Galisteo dike) have been identified (Peters and McIntosh, 1999). In the Cerrillos Hills, the intrusions are flanked by volcaniclastic strata of the Oligocene Espinaso Formation (Figs. 1B and 2), the composition of which records the two episodes of volcanism (Smith et al., 1991). The Espinaso Formation rocks represent relatively proximal volcaniclastic aprons associated with volcanic-vent complexes and consist of debris-flow deposits, small-volume discontinuous pyroclastic flow deposits, pyroclastic-fall deposits, and minor lavas (Smith et al., 1991).

PALEOMAGNETIC SAMPLING AND LABORATORY ANALYSIS

Paleomagnetic samples were collected from Tertiary intrusive rocks of the Cerrillos Hills, the Ortiz Mountains, and near La Cienega (Figs. 1A and 2). In addition, volcaniclastic breccias from the Oligocene Espinaso Formation were also sampled. Individual samples were collected as 2.5-cm-diameter cores using a water-cooled portable drill equipped with a diamond-coated bit, with between 6 and 12 samples obtained at each site. Sample orientations were made using magnetic and solar compasses prior to core extraction.

In the laboratory, the samples were cut into one or more 2.5-cm-long specimens. To fully characterize the remanent magnetization of the samples, at least one specimen from each sample was subjected to progressive alternating field (AF) demagnetization, usually to fields greater than 80–100 mT, depending on the coercivity spectra of individual samples. A subset of samples was subjected to either alternating field followed by thermal demagnetization or standard thermal demagnetization. Following demagnetization, the results of individual experiments were inspected and analyzed using a combination of orthogonal vector diagrams, equal-area projections, and normalized intensity decay plots. Characteristic remanent magnetization (ChRM) directions were determined using principal components analysis (Kirschvink, 1980). In cases where a stable end point, defined by three or more points on an orthogonal vector diagram defining a well-defined linear demagnetization interval, could not be fully isolated during either AF or thermal demagnetization due to overlapping components of magnetization, great circles were fitted to curvilinear demagnetization trajectories (Halls, 1976; Bailey and Halls, 1984; McFadden and McElhinny, 1988). For sites dominated by stable end-point behavior, site-mean directions were estimated using standard Fisher (1953) statistics; for sites in which the ChRM could not be isolated for all samples, a combination of stable end-point and great circle analysis (McFadden and McElhinny, 1988) was used to determine the best estimate of the site-mean direction. The quantification of discordance parameters for analysis of rotations in directional space followed the methods of Beck (1980), Demarest (1983), and Beck (1989).

The carriers of remanent magnetizations were determined using a combination of paleomagnetic and rock magnetic methods, including acquisition of a saturation isothermal remanent magnetization (SIRM), AF demagnetization of natural remanent magnetization (NRM), and thermal demagnetization of three-component IRM (Lowrie, 1990). In addition, characteristics of the laboratory unblocking temperatures of the ChRM as well as thermomagnetic measurements of low field magnetic susceptibility versus temperature analysis were also used.

RESULTS

Intrusive Rocks

The NRM intensity of Tertiary intrusive rocks from the Española Basin and surrounding areas is variable. Intensities for rocks of the Cerrillos Hills ranged from 0.0022 A/m to 96.3 A/m, with a geometric mean of 0.64 A/m. In the Ortiz Mountains, the intensity of intrusive rocks range from 0.07 A/m to 20.8 A/m (geometric mean = 0.75 A/m), whereas intrusive rocks from the La Cienega area range from 0.058 A/m to 4.78 A/m (geometric mean = 0.78 A/m).

Most samples from intrusive rocks gave demagnetization results that are straightforward and readily interpretable (Fig. 3). During demagnetization experiments, secondary
magnetizations are of north declination and moderate positive inclination or are randomly oriented and typically removed by low AF fields or temperatures. These secondary magnetizations probably represent viscous remanent magnetizations acquired in the present-day or laboratory fields. Despite the high-quality results from most intrusive rocks, several sites proved to be paleomagnetically unstable and were characterized by erratic directional and intensity changes during either AF or thermal demagnetization (e.g., sample E-70-10a, Fig. 3). These results cannot be interpreted, and samples showing this behavior were excluded from further analysis.

Samples that yielded acceptable behavior during progressive demagnetization were usually characterized by well-defined decay of the magnetization toward the origin of an orthogonal vector diagram (stable end-point behavior) during AF or thermal demagnetization (Fig. 3). Characteristic remanent magnetization (ChRM) directions, defined by stable end points consisting of three or more collinear points on the vector diagram and determined using principal components analysis, are of north declination and moderate positive inclination or south declination and moderate negative inclination. Some sites yielded more complicated behavior during demagnetization, yielding curvilinear demagnetization behavior on vector diagrams and directional trajectories on equal-area projections that defined great circle paths (Fig. 4), and failed to yield stable end-point behavior. This behavior is characteristic of two or more magnetizations of overlapping coercivity and/or unblocking temperature spectra such that the ChRM cannot be fully isolated.

For sites in which the ChRM of individual samples is well defined, site-mean directions were defined by Fisher (1953) statistics. For sites in which the ChRM of all samples could not be isolated, great circle and stable end-point data were combined to estimate the site-mean direction using the method of McFadden and McElhinny (1988); examples in which stable end-point and great circle data have been combined are shown in Figure 5. Site-mean directions determined by either method are well defined; \( \alpha_{95} \) values ranged from 1.4° to 12.3°, with most less than 6°, and precision parameter (\( k \)) values ranged from 1045 to 13.6 (Table 3).
Responses to AF and thermal demagnetization demonstrated a range of demagnetization behaviors, indicating considerable variation in the carriers of the ChRM in individual samples. AF demagnetization of magnetizations of low to moderate coercivity and maximum laboratory unblocking temperatures of 540 °C to 585 °C are indicative of low-titanium magnetite. However, many samples reveal higher coercivities (median destructive fields >70 mT) and unblocking temperatures between 600 °C and 640 °C (Fig. 3). These results indicate that the ChRM of some samples is carried by maghemite and/or hematite. Curves showing the acquisition of IRM indicate that most samples are dominated by magnetic phases that saturate between 150 and 250 mT, consistent with a relatively low coercivity phase such as magnetite (Fig. 6). The failure of some samples to fully saturate in fields in excess of 1.2 T confirms the presence of high-coercivity phases.

Figure 3. Orthogonal vector diagrams showing examples of demagnetization behavior of samples from Tertiary intrusive rocks of the Cerrillos Hills and surrounding areas. Solid symbols are projections on the horizontal plane; open symbols are projections on the vertical plane. Most results from intrusive rocks are straightforward and readily interpretable. Sample E-70-10a shows an example of highly erratic behavior for a sample in which the remanent magnetization cannot be interpreted; such samples were not used in the analysis. In situ coordinates. NRM—natural remanent magnetization.
Figure 4. Equal-area projections and orthogonal vector diagrams illustrating behavior of paleomagnetic samples in which a stable end point could not be readily isolated during demagnetization due to the presence of a high-intensity secondary component of magnetization with coercivity and laboratory unblocking temperature spectra that overlap that of the primary magnetization. For equal-area projections, solid symbols and lines are projections on the lower hemisphere; open circles and dashed lines are projections on the upper hemisphere. For vector diagrams, solid symbols are projections on the horizontal plane, and open symbols are projections on the vertical plane. In situ coordinates. NRM—natural remanent magnetization.

Figure 5. Equal-area projections of data for sites E-47 and E-30 illustrating site-mean directions (circles) and their $\alpha_{95}$ cone of confidence estimated through combination of paleomagnetic data from stable end points (squares) determined using principal components analysis and remagnetization circles (gray lines) using the method of McFadden and McElhinny (1988). Thick solid and dashed arcs are projections of sample demagnetization paths through data points for samples in which the stable end point could not be fully isolated due to the presence of a secondary magnetization of overlapping coercivity and laboratory unblocking temperature spectra; thin lines show projections beyond the data points. Solid lines and filled symbols are projections on the lower hemisphere; open symbols and dashed lines are projections on the upper hemisphere. In situ coordinates.
such as hematite. Thermal demagnetization of three-axis IRMs (Lowrie, 1990) (Fig. 7) shows that the intermediate-coercivity (0.3 T) IRMs are typically the highest in intensity and that they are mostly unblocked by laboratory temperatures of 520 °C to 580 °C. Unblocking temperatures in excess of 600 °C are shown by some samples, consistent with the results from the IRM acquisition experiments. Low-field susceptibility versus temperature experiments (Fig. 8) also show a wide range in behaviors, from single curves showing Curie temperatures of ~580 °C, consistent with pure magnetite, to mixed assemblages characterized by magnetite and a phase with a significantly higher Curie temperature near 640 °C (sample E-47-4a, Fig. 8), to curves showing only a phase with a Curie temperature of 640 °C (E-74-4a, Fig. 8). Heating curves for all samples are irreversible and show the breakdown or generation of magnetic phases during cooling. Overall, the rock magnetic data are consistent with a mixture of magnetic phases carrying the remanent magnetization in samples from the Cerrillos Hills and surrounding areas.

Volcaniclastic Rocks

Paleomagnetic results from volcaniclastic rocks of the Espino Formation are highly variable in their response to AF or thermal demagnetization. Samples were collected from clasts of both monolithic and heterolithic breccias. NRM intensities for measured clasts ranged from 0.027 A/m to 7.21 A/m, with a geometric mean of 1.01 A/m. Sites in heterolithic breccias failed to yield usable paleomagnetic data; samples yielded either ChRM directions that were randomly oriented or magnetizations that were paleomagnetically unstable. Consequently, most of the collection was abandoned from further analysis. However, four sites in breccias (three from the southern flank of the Cerrillos Hills and one in the Hagan Basin) yielded magnetizations that were well defined and well grouped. For these sites, most clasts (and matrix from site ER-1; Table 2) showed well-defined demagnetization behavior during AF and thermal demagnetization characterized by ChRMs of southeast declination and moderate negative inclination (Fig. 9A). The ready isolation of the paleomagnetic vector of these samples during AF demagnetization and complete unblocking at temperatures below 590 °C suggest that the remanence in these samples is probably carried by magnetite.

The ChRM directions from sites in these breccias are well grouped with $\alpha_m$ values of 2.6–8.4° and $k$ values of 34–100 (Table 3; Fig. 9B). The breccias sampled at these four sites are typically predominantly monolithic, and some deposits contain clasts that display radially oriented prismatic thermal contraction cracks associated with emplacement at high temperature. These deposits probably represent the products of small-volume block-and-shaft flows and/or related debris flows associated with emplacement of volcanic domes associated with the Espino Formation, consistent with the interpretation of Smith et al. (1991). Sites in which remanent magnetization directions are well defined but randomly distributed...
probably represent volcaniclastic deposits deposited at relatively low temperatures, perhaps as low-temperature debris flows and sheet floods. Site-mean directions for these rocks (Table 3) have been corrected for the orientation of intercalated fine-grained sedimentary rocks. A fold test on the volcaniclastic rocks, including sample E-45, which has no measurable dip, yields an in situ mean of $D = 145.8^\circ, I = -42.8^\circ$ ($k = 19.7, \alpha_95 = 21.2^\circ$) and a tilt-corrected mean of $D = 157.2^\circ, I = -50.1^\circ$ ($k = 15.2, \alpha_95 = 24.4^\circ$). The fold test is inconclusive at the 95% confidence level due to the small number of sites and minimal variation of structural attitudes.

**DISCUSSION**

Most sites sampled in the Cerrillos Hills and surrounding area yield well-defined magnetizations that are well grouped at the site level (Fig. 10A; Table 3). In situ site-mean directions, with the exception of some breccias that have been tilt corrected, are similar to expected middle Tertiary normal and reverse polarity reference directions for the study area (Table 1). Subequal numbers of normal and reverse polarity sites are present. The presence of dual polarity magnetizations indicates that remanence acquisition in the volcaniclastic and intrusive rocks of the Cerrillos Hills and surrounding areas spanned at least two polarity cycles. Two sites (E-68 and E-71, Fig. 10A) yield magnetizations that are significantly shallower in inclination than the others. We suspect that these sites may record transitional field directions recorded during a polarity reversal or field excursion. Given the discordance of these sites with respect to the others, we have excluded these sites from calculation of group-mean directions. The normal polarity site-mean directions from the Cerrillos Hills are well grouped about a group mean of $D = 345.6^\circ, I = 61.6^\circ$ ($k = 53.1, \alpha_95 = 4.3^\circ$, $N = 22$ site means) (Fig. 10A). The normal polarity site-mean directions appear to show little of the streaking about a northeast-southwest axis that Brown and Golombek (1986) reported for their normal polarity data from the Española Basin. In contrast, the reverse polarity site-mean directions from this study, although well defined at the site level, are more dispersed and are distributed about a northeast-southwest axis. To some extent, this may reflect contamination of the reverse polarity magnetization by normal polarity overprints that were not fully removed during demagnetization. This seems unlikely, however, given the largely single-component character of most of these samples, but it cannot be ruled out. The 19 reverse polarity sites give an in situ group mean of $D = 155.8^\circ, I = -57.0^\circ$ ($k = 25.2, \alpha_95 = 6.8^\circ$).

Despite the apparent streaking of the reverse polarity site-mean directions, inversion of the reverse polarity data to normal polarity (Fig. 10B) results in a positive class B reversals test (class $R_y = 6.78, r = 11.37$) based on simulation following the method of McFadden and McElhinny (1990). Together, the 41 normal and reverse polarity site-mean directions from the Cerrillos Hills intrusions give a grand-mean direction of $D = 340.9^\circ, I = 59.6^\circ$ ($k = 33.9, \alpha_95 = 3.9^\circ$). Taking an average of the virtual geomagnetic poles (VGP) from individual site-mean directions yields a mean pole at $74.0^\circ$N, 191.5$^\circ$E ($K = 18.0, A_95 = 5.4^\circ$). Geochronologic data from intrusive and volcanic rocks in the Española Basin show that magnetism spanned some 8–10 Ma, a period of time sufficient to average paleoserosal variation. The presence of antipodal dual polarity magnetizations, the wide range of rock types sampled, and the fact that these rocks are generally not well sorted suggest that the anomalously shallow directions from the Cerrillos Hills reflect the presence of a coherent remanent magnetic field that formed prior to 40 Ma.
the duration of magmatism, and the observed dispersion of the VGP data set suggest that the paleomagnetic data have likely averaged paleosecular variation. The angular standard deviation (S) of the poles is 19.1°, which is somewhat greater than would be expected scatter of ~15.5° for the 30 Ma paleolatitude of the study area (39°) using paleosecular variation model G of McElhinny and McFadden (1997) based on VGP scatter from the past 5 Ma. However, Model G values are strictly valid only for VGPs derived from lavas, which provide spot readings of the geomagnetic field, and they may not be appropriate when applied to plutonic rocks. Estimates of S from plutonic rocks are commonly less than predicted values, which probably results from some averaging of paleosecular variation at the site level during cooling and magnetization blocking (Frei et al., 1984; Harlan et al., 1994). Arguments based on estimates of S to support the averaging of paleosecular variation by data sets from tectonically complicated areas or that are complicated for other reasons have to be viewed with caution because complications in data sets (faulting, inability to correct for unrecognized tilting, etc.) may lead to estimates of S that are artificially large, thus leading to erroneously large inferences regarding the reliability or quality of specific data sets. This is a potential problem with the Espinosa data set in that the reverse polarity site-mean directions show a streaking both in directional and pole space. Nonetheless, the overall agreement of the normal and reverse polarity group mean directions suggests that this is likely not a problem in this case, and that the grand-mean direction from the Cerillos Hills rocks represents a reliable record of the middle Tertiary geomagnetic field.

Paleomagnetic results from the Orizt Mountains consist of six site-mean directions, five of which are of normal polarity and one of reverse polarity (Fig. 10C; Table 3). The mean of the normal polarity sites is \( D = 356.7°, I = 50.2° (k = 31, \alpha_95 = 14.0°), \) and the single reverse polarity site is \( D = 161.0°, I = -43.0° (k = 155, \alpha_95 = 3.5°, n = 8 \) samples). Together, these pass a class C reversals test (class Rci; \( \gamma_95 = 12.9°, \varphi = 34.3° \)), with a combined mean of \( D = 353.8°, I = 49.2° (k = 33.3, \alpha_95 = 11.8°, N = 6 \) sites). Paleomagnetic results from the La Cienega area include three sites from a small felsic intrusion and an isolated andesite sill (Fig. 10D; Table 3). The intrusion gives a mean group of \( D = 326.4°, I = 55.6° (k = 268, \alpha_95 = 5.6°), \) whereas the sill gives a site-mean direction of \( D = 22.4°, I = 61.3° (k = 130, \alpha_95 = 4.3°, n = 10 \) samples). The two sets of directions have not been combined because they are distinct at the 95% confidence level.

We interpret the paleomagnetic data from the Cerillos Hills intrusive and volcanioclastic rocks to represent a well-defined record of the mid-Tertiary geomagnetic field that has averaged paleosecular variation. Determination of the extent to which the observed grand-mean direction from the Cerillos Hills records vertical-axis rotation requires comparison to an expected Oligocene reference direction for the Cerillos Hills area. Although there are several middle Tertiary poles for North America from which expected directions can be computed, we employ the 30 Ma synthetic average pole for North America (79.6°N, 187.9°E, \( A_{95} = 5.4° \)) of Besse and Courtillot (2002) as discussed previously. Although we prefer this reference direction, for comparison with the results of Brown and Golombek (1986), we also discuss our results relative to the 24–36 Ma reference pole utilized in their study, which was derived from the compilation of Irving and Irving (1982). For the Española Basin, the Besse and Courtillot (2002) 30 Ma pole gives an expected reference...
Paleomagnetism of Tertiary intrusive and volcaniclastic rocks

Results from the Ortiz Mountains and La Cienega areas are insufficient in number of independent recordings of the geomagnetic field to fully average paleosecular variation. However, to compare our new results with those of Brown and Golombok (1986), we combined these sites plus the site in the Hagan Basin with those of the Cerrillos Hills to provide an average rotation estimate for the southern Española Basin. This gives a grand-mean direction of $D = 342.9^\circ$, $I = 58.3^\circ$ ($K = 31.9$, $\alpha_95 = 3.5^\circ$, $N = 53$) (Fig. 11), with a mean pole at 75.6°N, 187.1°E ($K = 17.6$, $A_95 = 4.8^\circ$). This grand-mean direction is not significantly different than the result for the Cerrillos Hills; it is 2.1° ± 4.2° from the expected 30 Ma reference direction of Besse and Courtillot (2002) and gives R and F values of −4.8° ± 7.7° and −0.1° ± 4.8°, respectively (Table 2). However, when compared with the Brown and Golombok (1986) reference direction, the angular separation is 9.5° ± 3.6°, and R and F are −12.8° ± 6.2° and −6.3° ± 4.0°, respectively. This result is similar in the overall sense of apparent rotation to that reported by Brown and Golombok (1986), but it is more precise. However, the choice of reference pole used has a profound effect on the statistical significance of the estimate. If the Besse and Courtillot (2002) pole is used, the result is statistically indistinguishable from the expected direction. In contrast, use of the 24–36 Ma pole results in a statistically significant apparent CCW rotation of −12.8° ± 6.2°, −5° less than calculated by Brown and Golombok (1986). The concordance with the expected 30 Ma reference direction suggests that this part of the Española Basin has not been significantly affected by postemplacement tilting or significant vertical-axis rotations, but the result using the 24–36 Ma expected direction implies that a combination of tilting and/or rotation has occurred. As noted by Brown and Golombok (1986) and further discussed in Wawrzyniec et al. (2002), some counterclockwise rotation in parts of the Española Basin could be explained by strike-parallel displacement along basin-bounding and/or related structures that formed or were reactivated as part of Rio Grande rift formation. Alternatively, the slight discordance between the new Cerrillos Hills result and the 30 Ma and 24–36 Ma reference directions could be explained by tilting of the upper crust or rotation about an inclined axis as suggested by Salyards et al. (1994).

To assess these possibilities and provide further insight into the tectonic and kinematic evolution of the Española Basin, we explore the possibility that the slight discordance in the observed paleomagnetic direction is due to minor postemplacement tilting of the Cerrillos Hills area. The entire study area lies east of the La Bajada (formerly Rosario) fault system, a north- to northwest-trending, west-dipping
structural zone that is one of the major structures defining the eastern margin of the Rio Grande rift at this latitude (Kelley, 1982; Thompson et al., 2006). At the latitude of the Cerrillos Hills and vicinity, footwall rocks of the La Bajada fault system range from the Middle Jurassic Entrada Sandstone to the lower Upper Cretaceous Mesaverde Formation, and these rocks are uniformly tilted by 10° to 20° to the east to east-northeast (e.g., Stearns, 1953; Kelley, 1979). In addition, north and east of Madrid, strata of the Galisteo Formation as well as Espinasto volcaniclastic rocks are also tilted to the east by comparable magnitudes. At La Bajada Hill, the Mesozoic section in the footwall of the La Bajada fault is nonconformably overlain by the horizontal Basalt of Mesita de Juana Lopez (Thompson et al., 2006), part of what they described as the early phase (ca. 2.6 Ma) of the Cerros del Rio volcanic field. If the observed east tilting of the footwall to the La Bajada fault system took place after emplacement of the Cerrillos Hills and associated igneous rocks and clearly before eruption of the flat-lying late Pliocene basalts, then at least much of the minor discrepancy in the paleomagnetic directions is due to slight post-remanence acquisition tilting. The idea that some tilting has affected the Cerrillos Hills intrusions is consistent with interpretations of aeromagnetic data by Grauch and Bankey (2003). Based on estimates of depths to the contact of Santa Fe Group rocks and Oligocene volcanic rocks, their interpretation indicates that Oligocene volcanic rocks dip northward into the Española Basin in a broad, asymmetric north-plunging syncline. The intrusive rocks of the

Figure 9. (A) Orthogonal vector diagrams showing demagnetization behavior of samples from volcaniclastic breccias from the Oligocene Espinasto Formation. Conventions are as in Figure 3. (B) Equal-area projection showing paleomagnetic results from individual clasts in a monolithologic breccia from the Oligocene Espinasto Formation in the Cerrillos Hills; stratigraphic coordinates. Individual samples yield defined single-component magnetizations of high laboratory unblocking temperatures. The demagnetization behavior of these samples and their well-grouped distribution indicate that the clasts were emplaced at high temperatures (i.e., >580 °C), probably as small-volume pyroclastic flows. Stratigraphic coordinates.
Cerrillos Hills primarily intrude the southwest flank of the syncline, and the generally east-dipping volcaniclastic strata sampled in this study are consistent with this interpretation.

A simple correction that restores the observed group-mean direction from the Cerrillos Hills with the expected 30 Ma reference direction of Besse and Courtillot (2002) for the study area requires a northeast-side-down tilt of 4.3° about a strike of 327°, generally consistent with, but significantly smaller than, estimates of minor east- to northeast-side-down tilting described already. This result would imply that most of the 10° to 20° tilting observed in the Mesozoic rocks described here is probably due to Laramide deformation prior to emplacement of the Cerrillos Hills intrusions. However, comparison with the 24–36 Ma reference direction of Brown and Golombek (1986) requires 12.5° of northeast-side-down tilting about a strike of 311°. Estimates of strike and dip based on depth to source interpretations of Grauch and Bankey (2003) suggest that the intrusions of the Cerrillos Hills and La Cienega may have been tilted 5° to 7° to the northeast about an average strike of 312°, similar to the corrections described previously herein. Correcting the Cerrillos Hills result for a 6° tilt thus yields $D = 340.5°, I = 59.8°, k = 25.2, \alpha_{95} = 3.8°, N = 42$. This brings the Cerrillos Hills mean direction into excellent agreement with the 30 Ma Besse and Courtillot (2002) expected direction (angular difference = $3.5° \pm 4.4°$), but it is still discordant with respect to the Brown and Golombek (1986) 24–36 Ma reference direction (angular separation = $9.5° \pm 3.8°$). Calculations of rotation estimates based on this tilt correction yield statistically insignificant R and F values for the 30 Ma Besse and Courtillot (2002) mean direction ($R = 1.3° \pm 7.1°, F = 2.0° \pm 4.4°$), whereas the rotation estimate based on the Brown and Golombek (1986) 24–36 Ma direction is greatly reduced but still statistically significant ($R = -6.7° \pm 6.5°$), and it largely eliminates the apparent flattening value (i.e., $F = -4.3° \pm 4.2°$).

A combination of in situ results from the Ortiz Mountains, tilt-corrected results from the Cerrillos Hills and La Cienega (using the
CCW rotation as a result of coupled left slip along the Pajarito-La Bajada–San Francisco–Sandia fault systems (western boundary) and the Pecos-Picuris fault (eastern boundary) (Fig. 12A). Given the geometry of the Española Basin, this left-slip couple was argued to have led to the formation of the Velarde graben (northwest corner), and the Santa Fe emplacement (southeast corner) of the structural block (northwest corner), and the Santa Fe embayment (southeast corner) of the structural block. Given the evidence for potential tilting, this grand-mean direction probably represents the best overall estimate of the paleomagnetic results for the Cerrillos Hills and related intrusions, and the best estimate of potential rotations that may have affected the Española Basin.

Although slight tilting could reconcile or reduce the apparent discordance of this paleomagnetic result with respect to expected Tertiary reference directions for the study area, it does not address the extensive evidence of apparent tectonic rotations recorded by other volcanic and intrusive rocks elsewhere within the Española Basin and surrounding areas (Fig. 12A). If we assume that the apparent discordance in paleomagnetic results from rocks of the Española Basin is entirely a reflection of CCW rotation, there are several ways in which to account for such rotation. Muehlberger (1979) hypothesized that the Española Basin experienced relatively young rigid block rotation as a result of coupled left slip along the Pajarito-La Bajada–San Francisco–Sandia fault systems (western boundary) and the Pecos-Picuris fault (eastern boundary) (Fig. 12A). Given the geometry of the Española Basin, this left-slip couple was argued to have led to the formation of the Velarde graben (northwest corner), and the Santa Fe embayment (southeast corner) of the structural block (northwest corner), and the Santa Fe embayment (southeast corner) of the structural block. Their argument was based on an extensive fault kinematic data set implying a west-to-northwest-oriented maximum elongation direction for mid-Tertiary and younger deformation along the plateau’s eastern margin. They postulated that, assuming an approximately west-to-northwest-oriented least principal stress direction for the area, left slip along the northeast-oriented Embudo and Tijeras-Canchoncito fault zones, as suggested by Muehlberger (1979), could be considered as an antithetic component of faulting to the dominant right slip along the north-trending western and eastern margins of the rift at this latitude. The orientation of originally roughly north-south–elongated structural blocks bounded by near north-south–trending zones of weakness, along which right slip took place, would be rotated in a CCW sense during dextral transtension (Fig. 12B).

If CCW rotation affected all or parts of the Española structural block, a key question is when did such rotations take place, in particular, in relation to different phases of Rio Grande rift extension? The data reported by Brown and Golombek (1986), Hudson et al. (2004), and Thompson et al. (2006) from the Pliocene-Pleistocene Cerros del Rio volcanic field suggest that the rotation of the southern Española block may be very young. In contrast, new paleomagnetic data and assessment of previous results from the ca. 1.6 Ma Otowi and ca. 1.2 Ma Tshirege Members of the Bandelier Tuff by Sussman et al. (2009) suggests that there has been no statistically significant variation in declination data from both tuff members across the Jemez Mountains and thus along the western margin of the rift. They conclude that processes responsible for any amount of vertical-axis rotation along the westernmost margin of the Española Basin must have ceased prior to ca. 1.6 Ma. If rotation has affected the more central parts of the Española Basin, it requires a very young age, and the CCW rotation would be consistent with an overall dextral transtensional deformation field related in a broad sense to regional latest Neogene tectonism in the western U.S. Cordillera (Humphreys and Coblenz, 2007).

CONCLUSIONS

Paleomagnetic data from mid-Tertiary intrusions of the Cerrillos Hills and some volcaniclastic rocks of the associated Espinosa Formation yield stable, well-defined remanent magnetizations. Both normal and reverse polarity magnetizations are present in these rocks and indicate that magmatic activity spanned at least two polarity chronos. The presence of antipodal magnetizations, the range or rock units sampled, the duration of magmatism in the Española Basin and surrounding areas, and the observed dispersion indicate that the data set has adequately averaged paleosecular variation and preserves a reliable record of the mid-Tertiary geomagnetic field at ca. 38–28 Ma. Paleomagnetic and rock magnetic data indicate that magnetite and/or maghemite carry the remanence in most samples. Correcting the paleomagnetic results for minor northeast tilt of the Cerrillos Hills and La Cienega intrusions yields a mean direction for Española Basin intrusions that is indistinguishable from the expected direction for the region based on the 30 Ma pole of Besse and Courtillot (2002), yielding an insignificant estimate of apparent CCW rotation of 1.8° ± 6.4°. In
contrast, comparison with the expected direction used by Brown and Golombek (1986) is permissive of minor CCW rotation (–6.2° ± 5.8°). This result is significantly less than their previous estimate, but it is consistent with rotation estimates of –9.6° ± 6.3° reported by Thompson et al. (2006) and Hudson et al. (2004) for Pliocene basalts of the Cerros del Rio volcanic field. Taken at face value, our results suggest that the middle Tertiary intrusive rocks in the Española Basin have experienced little or no CCW rotation, depending on the choice of reference direction used, and that postemplacement tilting during younger deformation has been minor.

The apparent sense of CCW rotation common to some paleomagnetic data sets from the Española Basin may be consistent with models of Muehlberger (1979) and Brown and Golombek (1986), who suggested that moderate left slip along rift-bounding faults segmented the rift into specific rotational blocks (i.e., Española block) (Fig. 12). Alternatively, a model that involves right slip of high-aspect ratio, elongated blocks oriented subparallel to the rift axis could also result in CCW rotation with increasing magnitudes of transtension (Wawrzyniec et al., 2002; Markley and Tikoff, 2002). The overall regional consistency of paleomagnetic results from several rock units of different age within the Española Basin, however, strongly suggests that CCW vertical-axis rotation is an important component of recent extension and deformation in the Rio Grande rift. If the paleomagnetic

Figure 12. Possible models to explain observed counterclockwise (CCW) rotations within the Española structural block. (A) Model proposed by Brown and Golombek (1986), following Muehlberger (1979), showing localities for which paleomagnetic data have been used to argue for the presence or absence of tectonic rotations. For each locality, the amount of apparent rotation relative to geographic north is shown by the heavy line; lines that are deflected to the left have experienced CCW rotations; those to the right have experienced clockwise (CW) rotations. The wedge-shaped area denotes the 95% confidence limit in the rotation value. Acronyms for localities are given in Table 2. (B) Model suggested by Wawrzyniec et al. (2002) showing how crustal blocks or sets of blocks may have rotated in a CCW sense during Neogene dextral transtension. T-CF—Tijeras-Cañoncito fault zone; PFZ—Pajarito fault zone; EF—Embudo fault zone; P-PF—Picuris-Pecos fault zone.
results from the Cerros del Rio volcanics (Hud-son et al., 2004) adequately average secular vari-
tion, then most of this deformation must have
occurred within the past 2 Ma. This study high-
lights the need for additional high-quality paleo-
metric data from the Española Basin that can
unequivocally be shown to fully average secular
variation. Integration of paleomagnetic data with
Global Positioning System (GPS) studies of the
modern-day extensional strain field is required
for fully document the nature, extent, and kine-
matics of rotation associated with ongoing Rio
Grande rift deformation.

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