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## *Contents*



A late Miocene Rio del Oso dike cross-cutting the light colored Miocene Ojo Caliente Sandstone of the Tesuque Formation (Santa Fe Group). The Rio del Oso dike swarm is located in the Chili 7.5' quadrangle, western Española Basin, and crops out as backbone-like dikes cutting across the landscape in stark contrast to the Ojo Caliente sandstone. The western margin of the Rio Grande rift at the latitude of Española, NM, is characterized by a zone >17 km wide of oblique-slip faults. The dikes are tabular, fine grained, and mafic in composition (basalt). The dikes range from 0.5–3.5 m wide, form en echelon segments, and strike generally north-south. The minerals in hand samples are 1 mm- to 2 mm long, often with elongated geometries, and include olivine (vitreous luster and olive-green color), plagioclase (white to gray tabular crystals), and minute augite (stubby prisms) phenocrysts. Many of the dikes have vesicles that are often filled with secondary calcite. At a few locations elongated vesicles and lineations occur on the faces of the dikes. The dike mineralogy in thin section includes major Ca-plagioclase, augite, olivine, and magnetite. Swallowtail morphologies of the plagioclase laths as well as dendritic habit of the Fe-Ti oxide phases indicate undercooling of the host magmas consistent with shallow emplacement and rapid cooling.

*—Field photo by Rhonda V. Trujillo.*


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# Paleomagnetic data bearing on vertical axis rotation of the Rio del Oso dike swarm, western Española Basin, New Mexico

*Petronis, M.S.*[1], *Trujillo, R.V.*[1, 2], *Lindline, J.*[1], and *Zebrowski, J.P.*[1]

[1]Environmental Geology, Natural Resources Management Department, New Mexico Highlands University, P.O. Box 9000, Las Vegas, NM 87701
[2]New Mexico Environment Department, Air Quality Bureau, 525 Camino de los Marquez, Suite 1, Santa Fe, New Mexico, 87505-1816

## Abstract

The Española Basin is one of a series of interconnected, asymmetrical basins in the Rio Grande rift that includes a number of north- and northeast-striking faults that accommodated block tilting and basin subsidence. The western margin of the Española Basin, in particular, is characterized by a greater than 17-km wide zone of normal and oblique-slip faults. To clarify the involvement of block rotation in the tectonic evolution of the Española Basin, we carried out a paleomagnetic study of mafic intrusions (Rio del Oso dike swarm) that are genetically related to regionally extensive basalt flows of the mid-Miocene Lobato Formation. The primary hypothesis tested was that these intrusions experienced some degree of vertical axis rotation associated with mid-Miocene to recent continental rifting. In situ paleomagnetic results from forty-two sites yield a group mean declination (D) of 344.0°, an inclination (I) of 41.1°, $\alpha_{95}$ of 6.1°, and *k* of 14.1. The group mean result is discordant to the <10 Ma pole of D=356.0°, I=54.4°, $\alpha_{95}$ = 3.3° with a statistically significant inferred rotation (R) of -12.0°± 7.2° and flattening of +13.3° ± 5.5° relative to the <10 Ma pole field direction. These discordant results indicate that a modest degree of counter-clockwise vertical axis rotation occurred in this region, which is likely associated with Rio Grande rifting north of the Jemez Mountains. It is possible that oblique motion along the Santa Clara fault and/or the Cañada del Almagre fault facilitated the vertical axis rotation. The results from this study imply that vertical axis rotation is common to extensional rift systems and should be considered when modeling continental extension.

## Introduction

The Rio Grande rift is a roughly north-south trending intracratonic rift that separates the over thickened and relatively undeformed continental crust of the Colorado Plateau on the west from the stable craton of the Great Plains to the east (Kelley, 1977; Aldrich and Dethier, 1990; Chapin and Cather, 1994). The rift extends south from about Leadville, Colorado and merges with the eastern Basin and Range Province of eastern Arizona, New Mexico, and northern Mexico (Fig. 1). Characteristics of the rift include high heat flow, structurally-controlled basins, crustal deformation, and Cenozoic to Holocene silicic to mafic volcanism. The high heat flow is attributed to upper mantle asthenospheric upwelling and thermal lithospheric erosion (Seager and Morgan, 1979; Morgan et al., 1986; Wilson et al., 2005). In northern New Mexico and southern Colorado, the structural manifestation of the rift is a series of right-stepping, asymmetric fault-bounded en echelon basins with extension increasing southward (Kelley, 1982). From north to south, these are the upper Arkansas River Basin, San Luis Basin, Española Basin, Albuquerque Basin, and the southern Rio Grande Basin (Fig. 1). Rift deformation from ca. 30 to 20 Ma resulted in a broad zone of distributed extension along low-angle faults, crustal doming, widespread magmatic activity, and accumulation of sediment in intrarift basins (Chapin, 1988; Prodehl and Lipman, 1989). Between ca. 20 and 10 Ma, the rate of extension accelerated with rifting 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 rate of extension has decreased in the last 5 Ma, but the rift remains seismically and magmatically active (Grauch et al., 2017). We hypothesize that Rio Grande rift faulting in the northwestern Española Basin was accommodated by extension and counter-clockwise rotation of fault-bounded crustal blocks. To assess this hypothesis, we obtained paleomagnetic data from Miocene mafic intrusions of the Rio del Oso dike swarm (Koning et al., 2007) in the western Española Basin. We also conducted petrographic examination of the studied intrusions to confirm their affinity to the regionally extensive extrusive basalts of the Lobato Formation.

## Geologic and tectonic history of the Española Basin

The Española Basin, located in north-central New Mexico, is bordered by the Nacimiento uplift to the west and the Sangre de Cristo Mountains to the east (Fig. 1). The Española Basin likely developed by about 26 Ma and was initially ~3 km deep during the Oligocene (Golombek et al., 1983). Renewed tectonism during the early Miocene resulted in localized faulting that led to significant accumulations of sediment in the north and central parts of the basin with thicknesses reaching up to 5 km (Aldrich, 1986; Golombek et al., 1983). The rift-basin deposits are collectively referred to as the Santa Fe Group. At approximately 10 Ma, basin subsidence slowed and sediment aggradation ensued, resulting in thick deposits of the Santa Fe Group within the Española Basin (Aldrich and Dethier, 1990). In addition, between 15 Ma and 14 Ma, volcanism occurred at the northwestern edge of the basin (Aldrich and Dethier, 1990) along the Jemez Lineament, a complex suture zone between the Mesoproterozoic Yavapai and the Mazatzal lithospheric provinces that facilitated volcanism and tectonism near the Jemez

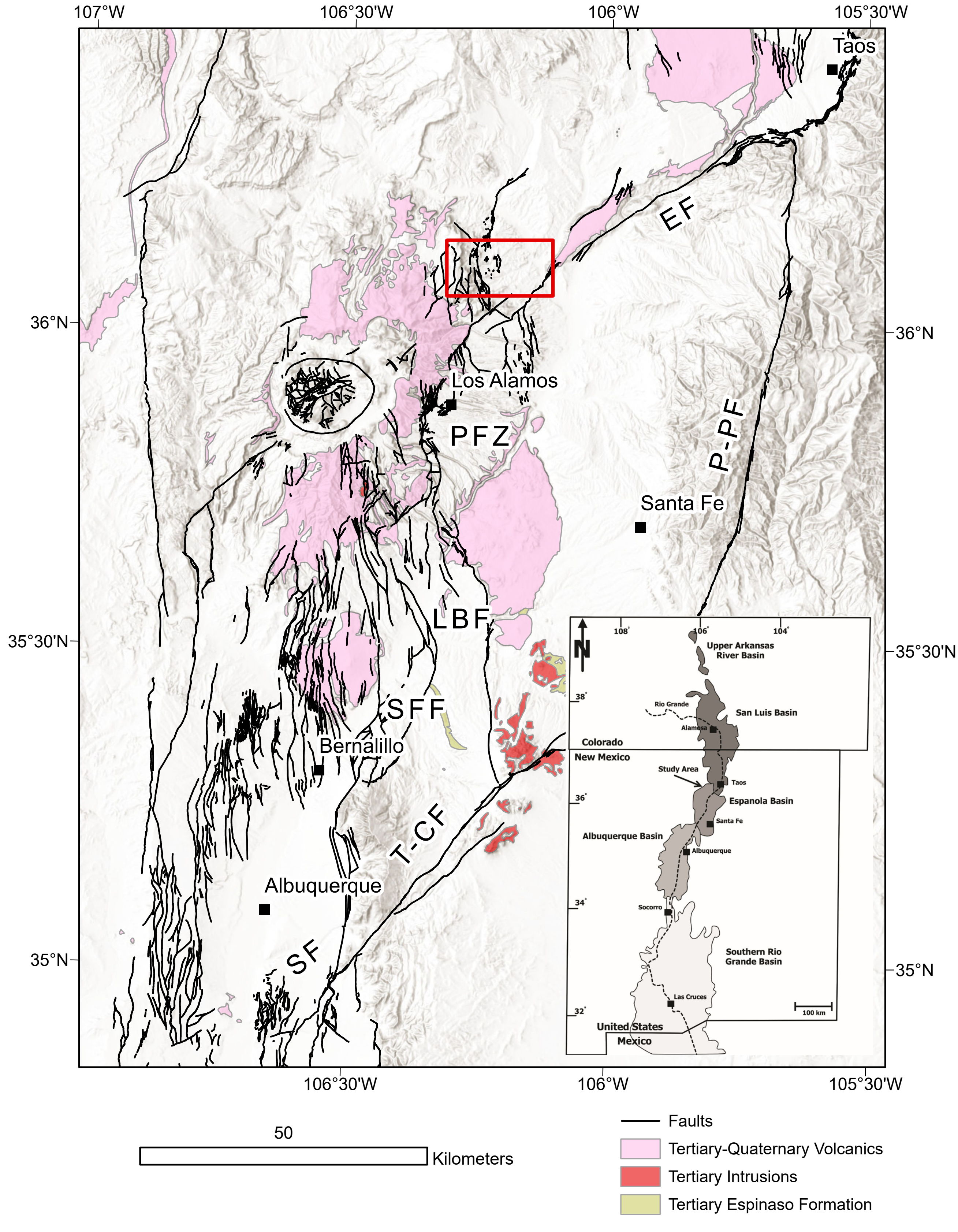


Figure 1. Inset: General sketch map depicting the Rio Grande rift and related sub-basins throughout southern Colorado, New Mexico, and Mexico (modified from Grauch and Bankey, 2003). Tectonic map of part of northern New Mexico showing the location of the the Española block. T-CF—Tijeras-Cañoncito fault zone; PFZ—Pajarito fault zone; EF—Embudo fault zone; P-PF—Picuris-Pecos fault zone; LBF—La Bajada fault; SFF—San Felipe fault; SF—Sandia fault. Red rectangle indicates area shown in the Figure 2 map. 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 NMBGMR (2003).

Mountains and locally throughout the Rio Grande rift (Aldrich, 1986; Wolff et al., 2005). Jemez Mountain volcanism began with the eruption of the Lobato Formation basalts from numerous vents until approximately 10 Ma. At ~9 Ma, volcanism slowed drastically with only minor Lobato volcanism continuing until ~7 Ma (Aldrich and Dethier, 1990). The end of basaltic volcanism in this area is thought to be related to a change in the regional stress field. This switch is evident throughout western North America and has been inferred to reflect reorganization of North American-Pacific plate boundary conditions (Golombek et al., 1983; Prodehl and Lipman, 1989; Atwater and Stock, 1998).

## Lobato Formation Basalts

The Lobato Formation basalts are the oldest unit of the Polvadera Group, which crops out on the northern to eastern flanks of the Jemez Mountains and forms prominent mesas throughout the area (Smith, 1938; Koning et al., 2005). The Lobato Formation consists of multiple flows, associated cinder deposits, and intrusive rocks (dikes and stocks) of primarily olivine basalt that yield K-Ar age determinations ranging from 14.05 ± 0.33 Ma to 7.6 ± 0.4 Ma (Dalrymple and Hirooka, 1965; Bachman and Mehnert, 1978; Luedke and Smith, 1978; Baldridge et al., 1980; Manley and Mehnert, 1981; Aldrich, 1986; Gardner et al., 1986) with a voluminous phase of volcanism occurring between 10.8 ± 0.3 Ma to 9.1 ± 0.2 Ma (Gardner et al., 1986). Lobato volcanism and associated intrusive magmatism occurred concurrently and was likely driven by tectonic activity associated with Rio Grande rifting. Across the region, eruption of the Lobato basalts likely occurred from at least four vents producing a number of large shield cones and possibly fissure vents. Individual flows are 2 to 5 meters thick, and interfinger locally with clastic sediments of the Santa Fe Group (Baldridge et al., 1980; Dethier and Manley, 1985). Intrusive bodies occur locally across the Española Basin, with a relatively large dike set (the Rio del Oso dike swarm) located in the Chili 7.5' quadrangle (Koning et al., 2005). Intrusions associated with Lobato Formation basalts contain 1 to 2 mm crystals of plagioclase, olivine, and augite.

## Geology of the Chili quadrangle

Dikes in the Rio del Oso swarm were studied in the northwest corner of the Chili quadrangle, which lies north of the intersection of the Jemez Lineament and the western margin of the Española Basin in Oso Arroyo just west of Chili, New Mexico (Fig. 1). The Chili quadrangle is situated in a structurally diverse part of the basin that exhibits a complex brittle kinematic history (Koning et al., 2005; Fig. 1). A variety of rift-related geologic features as old as middle Miocene are well-exposed in the area. These features include an array of normal and strike-slip faults, a relatively complete sequence of middle to upper Miocene and Pliocene rift-basin sediments, upper Miocene basaltic intrusions and lava flows, and a well-preserved set of Quaternary terraces (Koning et al., 2005). Major structures in the area include the Santa Clara Fault, a northeast-southwest striking, east-dipping sinistral oblique-slip fault located in the southern part of the Chili quadrangle; the Cañada del Amagre fault, which strikes north to northwest with dextral offset; and the dextral Guaje Mountain fault (Aldrich and Dethier, 1990; Koning et al., 2005). The Cañada del Amagre fault and the Guaje Mountain fault have comparatively large components of strike-slip relative to dip-slip motion, and suggest that the horizontal component of displacement along these faults may be related to counterclockwise rotation between structural blocks (Aldrich and Dethier, 1990) as demonstrated in numerous tectonic settings (Otofuji et al., 1985, Hudson et al., 2004, Petronis et al., 2002).

We collected samples from dikes in the Rio del Oso swarm (Fig. 2), which trend generally north-south and show both a right- and left-stepping en echelon geometry. En echelon dike systems are often argued to be interconnected at depth (e.g., Baer, 1991). Anderson (1951) proposed that dike segmentation may be attributed to rotation of the minimum principle stress ($\sigma 3$) toward the surface during magma intrusion. We sampled at least eight distinct intrusions at four locations spread over an ~4.8 km$^2$ area, although the number of sampled intrusions is a minimum estimate because of difficulty tracing individual dikes along strike. The dikes intrude Miocene Santa Fe Group deposits and form prominent ridges across the landscape (Fig. 3). The dikes have been dated by the K-Ar method to yield age estimates of 9.7 ± 0.3 Ma, 10.7 ± 0.3 Ma, and 10.6 ± 0.3 Ma (Baldridge et al., 1980). Likely correlative lava flows from the area have a similar mineralogy as the intrusions and yield age determinations that range from 9.6 ± 0.2 Ma to 12.4 Ma (Dethier et al., 1986, Dethier and Manley, 1985).

No detailed paleomagnetic studies have been conducted on the dikes in this area. In northern New Mexico, several paleomagnetic studies (Brown and Golombek, 1985, 1986; Salyards et al., 1994; Harlan and Geissman, 2009; Petronis and Lindline, 2011) have reported data supporting the presence of statistically significant vertical axis block rotations or lack thereof associated with Rio Grande rift extension (Table 1). Brown and Golombek (1986) reported counter-clockwise (CCW) rotation of intrusive rocks of the Ortiz porphyry belt within the Española Basin that yielded an apparent CCW rotation of –17.8° ± 11.4°. They postulated that the CCW rotations were the result of left-lateral slip along major faults bounding the rift (Muehlberger, 1979; Brown and Golombek, 1986). Salyards et al. (1994) conducted a paleomagnetic study within the Española Basin that concluded that the north-central Rio Grande rift is not rotating as a single unit, but rather as a number of smaller, independently CCW-rotating structural blocks. Aldrich and Dethier (1990) suggested that due to the large strike-slip components on the major faults in the Española Basin, it is probable that fault-bounded blocks have, and continue to undergo,

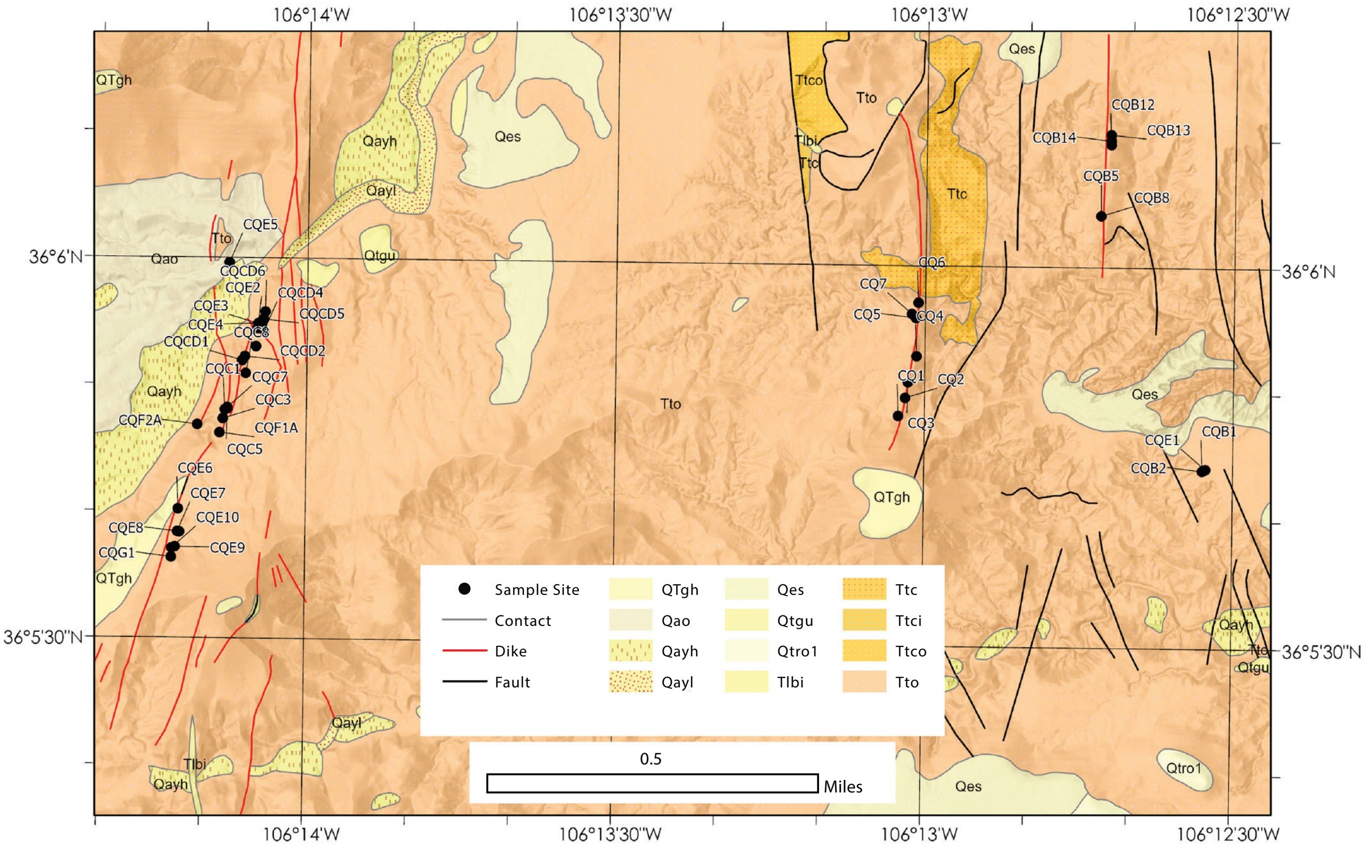


Figure 2. Geologic map (Koning, et al., 2005) of the area where the Rio del Oso dikes were sampled. See Table 2 for the paleomagnetic results from these sites.

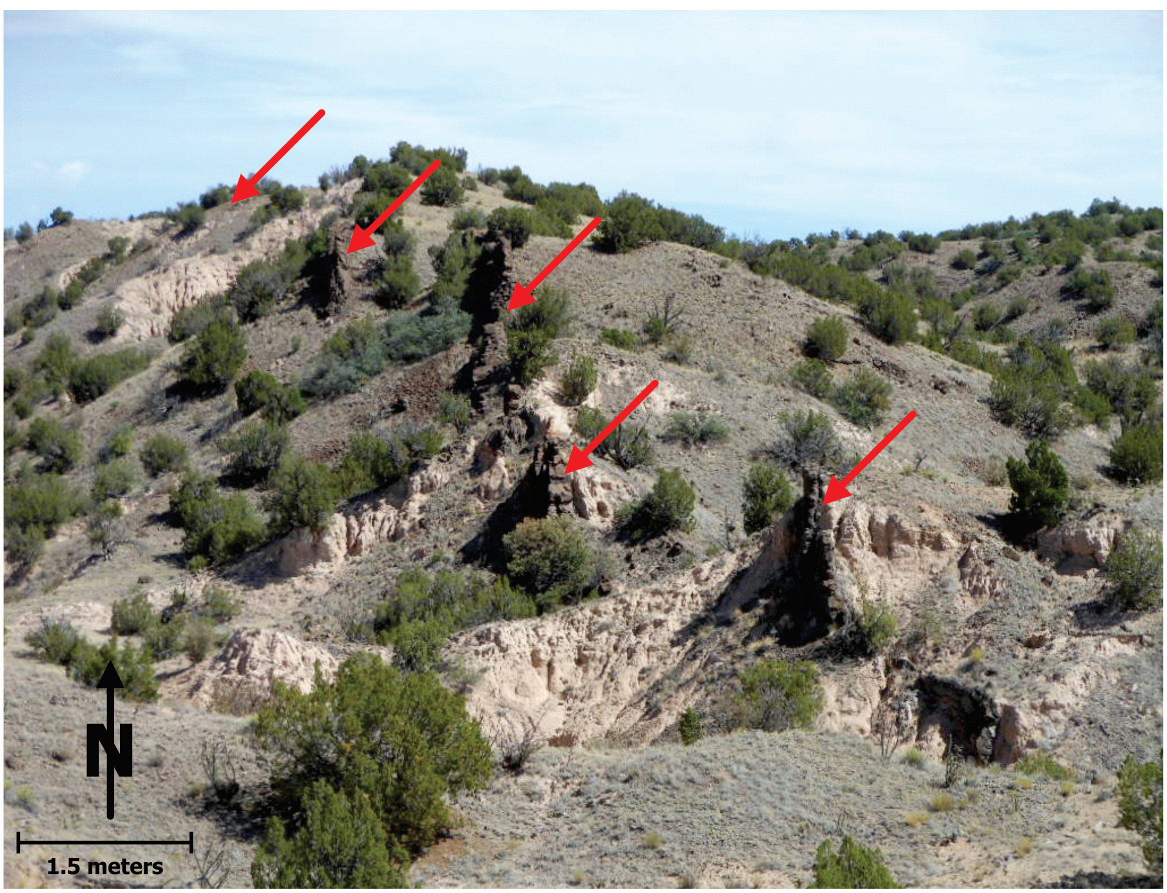


Figure 3. Field photograph of one of the studied dikes (red arrows) showing the common en echelon outcrop pattern.

significant vertical-axis rotation. Petronis and Lindline (2011) conducted a paleomagnetic study of an apparent monoclinal fold within the Lobato Formation basalts adjacent to the Santa Clara fault in the Chili quadrangle. They concluded, based on the results of a paleomagnetic fold test (Cox and Doell, 1960), that the lava flowed across a paleoescarpment into a paleovalley that existed adjacent to the Santa Clara Fault, with no evidence of vertical-axis rotation. Outside of the Española Basin, other studies have shown either negligible or statistically significant clockwise (CW) rotations. For example, Harlan and Geissman (2009) presented paleomagnetic data from in situ Tertiary intrusions and tilt-corrected volcaniclastic strata of the Oligocene Espinaso Formation, which yielded results indistinguishable from the 30 Ma reference direction for the study area. However, they argue that if an alternative reference direction is used, minor CCW rotation (–6.6° ± 5.8°) is possible. These studies show a complex image of crustal block rotation accompanying rift extension in northern New Mexico and likely in other rift systems world-wide. 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. The purpose of this study is to better assess possible block rotation in the western Española Basin and thus contribute to a better understanding of the kinematics of Rio Grande rift extensional dynamics.

Table 1: Paleomagnetic rotation estimates for the Española Basin and surrounding region.

| Paleomagnetic Studies | R± Δ R | F± Δ F | Source |
|---|---|---|---|
| CF: Chamita Formation | -11.5° ± 5.3° | 3.9° ± 5.1° | 6,7 |
| SFES: Chamita Formation | -11.1° ± 5.1° | N/A | 1 |
| SFTE: Tesuque Formation-Nambe Member | -0.6° ± 5.1° | N/A | 1 |
| SFAS: Tesuque Formation Skull Ridge Member | -5.0 ± 6.0° | N/A | 1 |
| SFSR: Nambe Member | -8.3° ±7.2° | N/A | 1 |
| SFCA: Chamita Formation | -28.5° ± 11.1° | N/A | 1 |
| CRV: Cerros del Rio Volcanics | -19.2° ± 14.8°; -14.7° ± 9.8° | -6.9° ± 6.9°; 2.5° ± 5.9° | 2,3 |
| TF: Tesuque Formation | -18.5° ± 5.8° | 4.0° ± 5.5° | 4,6 |
| CH3: Cerillos Hills–Ortiz Mounatins | 1.8 °± 6.4° | 3.0° ± 4.0 | 3 |
| *< 10 Ma Lobato Basalt | 7.2°± 14.3 | 0.9°±12.9° | 2 |
| *VR: Valles Rhyolite | 8.0° ± 9.2° | 1.5°± 8.4 | 5,6 |
| *TSF: Tschicoma Formation | 19.4°±13.9° | 2.7°±13.2 | 2 |
| *PCF: Paliza Canyon Formation | 11.9°±17.4° | 1.6°±16.0° | 2 |
| CQ: Chili Quadrangle Basaltic Dikes | -12.0°± 7.2° | +13.3°± 5.5° | This study |

EXPLANATION: Paleomagnetic studies are the site locations with published paleomagnetic data (* indicates site not shown on Figure 10B); R is the rotation and ΔR is the error (after Demarest, 1983); F is the flattening and ΔF is the error (after Demarest, 1983). 1, Salyards et al., 1994; 2, Brown and Golombek, 1985; 3, Harlan and Geissman, 2009; 4, Barghoorn, 1981; 5, Singer and Brown, 2002; 6, Brown and Golombek ,1986; 7, MacFadden, 1977.

# Methods

## *Field and laboratory sampling methods*

Field sampling began in October 2010 with eight to ten drill-core samples collected at fifty-seven sites (Fig. 2) across the area using a modified Echo 280E gasoline-powered drill with a non-magnetic diamond tip drill bit. All samples were oriented using a magnetic compass and, when possible, a sun compass. At each site, independent core samples were drilled along the margins and/or across the center of the dikes with the total number of samples collected at each site dependent on the level of exposure. All core samples were cut into 2.2 cm by 2.5 cm cylinder specimens using a diamond tipped, non-magnetic saw blade at New Mexico Highlands University's Rock Processing laboratory, with up to three specimens per core sample obtained. Drill site locations were precisely located using a Garmin GPS 60Csx (WGS84 datum). To characterize the magnetic mineralogy, we conducted a suite of laboratory experiments with the goal of identifying the magnetic phases carrying the remanence, and the overall ability of these rocks to faithfully record an ambient magnetic field. Equipment used included an AGICO JR6A dual-speed spinner magnetometer, ASC D-2000 (static) alternating field demagnetizer, and home-built and ASC Scientific (Model IM-10-30) static impulse magnets capable of 1 to 3 Tesla peak fields. All susceptibility and Curie point experiments were measured with an AGICO MFK1-A kappabridge susceptibility meter, with a CS4 high-temperature attachment at the New Mexico Highlands University Paleomagnetic-Rock Magnetic laboratory.

## *Rock magnetic experiments*

Curie point experiments were used to establish the dominant magnetic mineral phase(s) present in the sample and to define the composition of the titanomagnetite phase(s). The procedure was performed in steps of heating and cooling from 25°C to 700°C and back to 40°C in an argon atmosphere to minimize oxidation of the sample, using a CS4 furnace attachment for the MFK1-A at a rate of ~14°C/min. The inflection point method (Tauxe, 1998) and Hopkinson Peak method (Hopkinson, 1889; Moscowitz 1981) were used to interpret the Curie points. The most common magnetic minerals in igneous rocks and their respective Curie point temperatures include magnetite 575–585°C, hematite 680°C, and pyrrhotite 320°C. To characterize the domain state of the magnetic minerals, we conducted isothermal remanent magnetization (IRM) acquisition experiments, which may be used to characterize the composition and the grain size of the ferromagnetic mineral(s) that are responsible for carrying the remanence and the stability of the magnetization (Butler, 1992; Dunlop, 1972, 1981; Dunlop et al., 1973). These experiments involve 17–20 magnetization steps to a peak field of 2.5 T. After a specimen reached saturation, an increasingly larger back-field was applied. The back-field was increased until net magnetic moment reached a remanence of zero; the applied field at which the magnetic moment was reduced to zero is the coercivity of the remanence. Back-field IRM (BIRM) typically involved 5–10 demagnetization steps up to 0.06 T. The shape of the IRM acquisition and the BIRM curves aided with identifying the grain composition (e.g., titanomagnetite, titanomaghemite, hematite), the magnetic grain size, and the domain state (single domain, pseudosingle domain, or multidomain) of the dominant magnetic mineral phase present (Dunlop, 1972, 1981; Dunlop et al., 1973).

### *Paleomagnetic methods*

Samples were progressively demagnetized in an alternating field, and the remanent magnetization measured, typically in 10 to 25 steps to a maximum field of 120 mT using a ASC Scientific D-TECH 2000 AF-demagnetizer. Samples with high coercivity were treated with thermal demagnetization (TH) up to a maximum of 630°C, with most samples being fully demagnetized at 580°C. Thermal demagnetization experiments on replicate specimens, to compare with AF demagnetization behavior, were conducted with an ASC Scientific TD48 thermal demagnetizer. Principal component analysis (Kirschvink, 1980) was used to determine the best-fit line through selected demagnetization data points for each sample using Remasoft 3.0 (Chadima and Hrouda, 2006) (Fig. 4; Table 2). For most samples, a single best-fit line to the demagnetization data was obtained. Best-fit magnetization vectors involved 5 to 18 data points, but as few as 3 to as many as 25 were used,

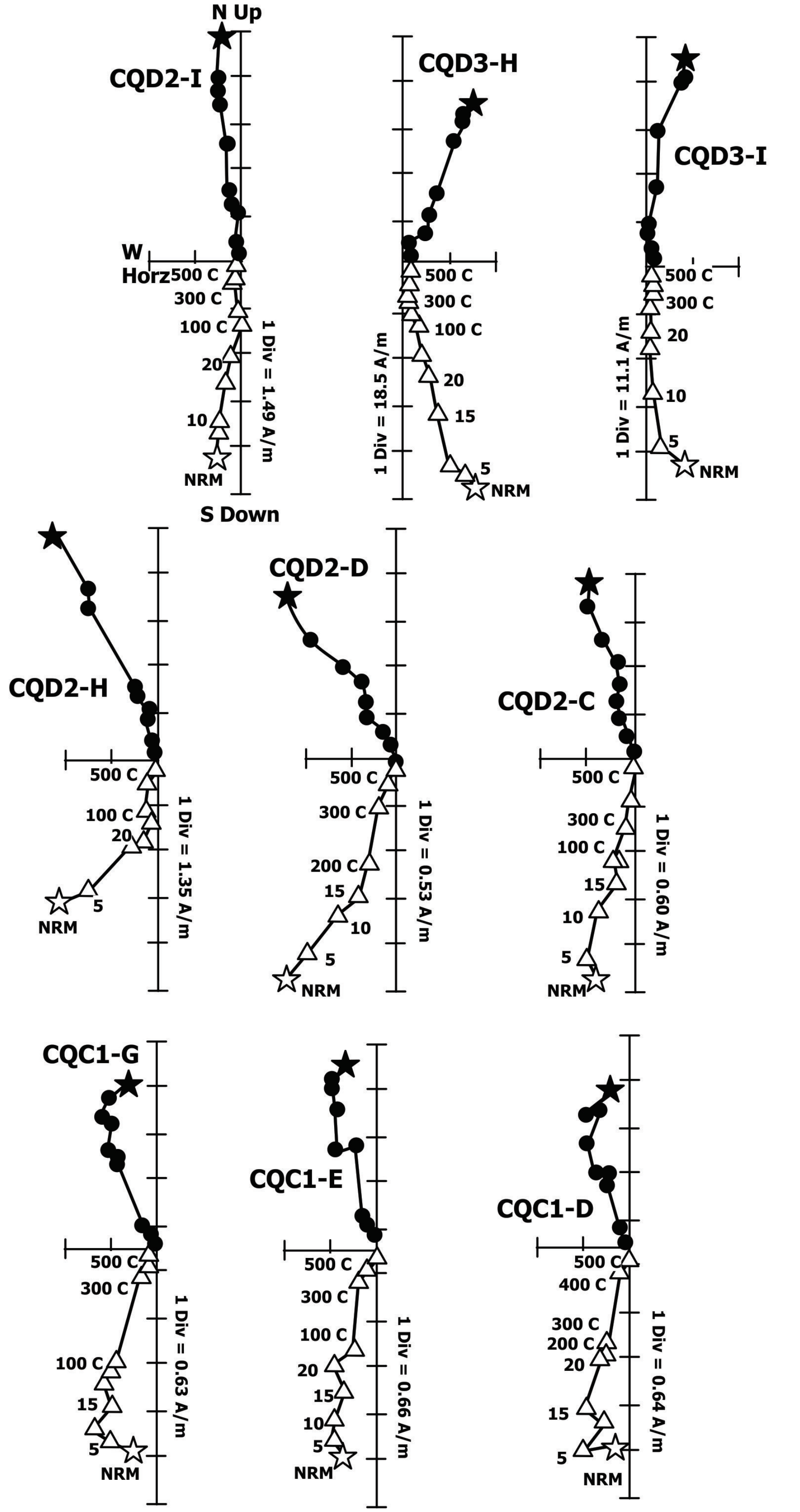


Figure 4. Orthogonal demagnetization diagrams (Zijderveld, 1967) showing alternating field and thermal demagnetization behavior of representative samples. Each sample was demagnetized from 5 to 20 mT in 5 mT steps, and from 100° to 500°C in 100°C steps. Declinations are plotted on the horizontal plane (circles) and inclinations are plotted on the vertical plane (triangles). Individual steps (mT, °C) are labeled on the vertical plane.

Table 2. Paleomagnetic data from the Rio del Oso dike swarm, Chili Quadrangle, Española Basin, NM.

| SITE | N | No | R | $\alpha_{95}$ | *k* | Dec | Inc | VGB Lat | Long | UTM Northing | Easting |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **CQ1** | 7 | 7 | 6.95 | 5.7 | 111.9 | 359.1 | 45.3 | 80.4 | 79.2 | 390359 | 3995374 |
| **CQ2*** | 4 | 8 | 3.51 | 40.7 | 6.1 | 340.8 | 43.1 | 70.2 | 135.2 | 390376 | 3995418 |
| **CQ3** | 5 | 7 | 3.93 | 6.0 | 163.6 | 356.4 | 12.2 | 59.7 | 81.7 | 390383 | 3995457 |
| **CQ4D** | 8 | 8 | 7.97 | 3.6 | 241.4 | 342.2 | 50.3 | 74.1 | 149.5 | 390404 | 3995519 |
| **CQ5B** | 6 | 8 | 4.90 | 3.9 | 296.1 | 335.3 | 45.2 | 66.7 | 146.7 | 390403 | 3995612 |
| **CQ6B** | 7 | 8 | 6.32 | 8.7 | 49.1 | 335.8 | 21.1 | 56.1 | 121.9 | 390409 | 3995649 |
| **CQ7A** | 5 | 8 | 3.96 | 10.7 | 75.2 | 350.2 | 55.4 | 81.9 | 162.7 | 390393 | 3995622 |
| **CQ7B** | 8 | 8 | 7.94 | 5.4 | 107.8 | 336.1 | 44.4 | 67.1 | 143.8 | 390393 | 3995622 |
| **CQ7C** | 8 | 8 | 7.88 | 7.4 | 57.6 | 350.0 | 46.2 | 77.8 | 120.8 | 390393 | 3995622 |
| **CQB1** | 8 | 8 | 7.95 | 4.7 | 141.6 | 344.2 | 46.1 | 73.9 | 135.6 | 391097 | 3995238 |
| **CQB2** | reject | - | - | - | - | - | - | - | - | 391097 | 3995238 |
| **CQB3*** | 4 | 8 | 3.75 | 27.4 | 12.2 | 328.9 | 27.1 | 54.7 | 133.8 | 391097 | 3995238 |
| **CQB4** | 5 | 8 | 4.99 | 3.7 | 634.7 | 333.1 | 43.2 | 64.4 | 145.7 | 390853 | 3995859 |
| **CQB5*** | 5 | 8 | 4.43 | 31.2 | 7.0 | 357.4 | -15.4 | 46.2 | 78.1 | 390856 | 3995857 |
| **CQB6** | 7 | 8 | 6.90 | 7.9 | 59.5 | 339.4 | 41.7 | 68.6 | 135.3 | 390858 | 3995856 |
| **CQB7** | 5 | 8 | 3.28 | 5.1 | 226.1 | 355.4 | 30.1 | 69.5 | 87.6 | 390859 | 3995855 |
| **CQB8** | 6 | 8 | 5.98 | 3.8 | 319.9 | 342.2 | 46.9 | 72.9 | 141.5 | 390860 | 3995854 |
| **CQB8_2** | 5 | 8 | 4.98 | 5.2 | 214.3 | 344.3 | 48.9 | 75.2 | 143.6 | 390861 | 3995853 |
| **CQB9** | 6 | 8 | 5.97 | 5.2 | 169.4 | 339.1 | 42.1 | 68.4 | 136.3 | 390862 | 3995852 |
| **CQB10** | 8 | 8 | 7.78 | 10.1 | 31.3 | 272.2 | 68.5 | 28.8 | 208.9 | 390864 | 3995854 |
| **CQB11** | reject | - | - | - | - | - | - | - | - | 390866 | 3995851 |
| **CQB14** | 8 | 8 | 7.90 | 6.6 | 71.7 | 332.3 | 46.2 | 64.7 | 151.6 | 390878 | 3995041 |
| **CQB15** | 5 | 8 | 3.98 | 6.7 | 191.7 | 332.1 | 14.7 | 51.8 | 122.5 | 390878 | 3995041 |
| **CQC1** | 5 | 8 | 4.97 | 6.5 | 138.6 | 339.1 | 47.8 | 71.0 | 148.0 | 390724 | 3995391 |
| **CQC2** | 6 | 8 | 5.96 | 6.4 | 112.1 | 348.7 | 48.1 | 78.4 | 129.6 | 390724 | 3995391 |
| **CQC3** | 7 | 8 | 3.92 | 14.8 | 39.7 | 339.9 | 47.9 | 71.8 | 146.7 | 390719 | 3995369 |
| **CQC5** | 5 | 6 | 4.97 | 7.1 | 118.3 | 345.1 | 54.2 | 77.7 | 160.9 | 390730 | 3995393 |
| **CQC6** | 6 | 7 | 5.94 | 7.6 | 78.0 | 344.9 | 45.9 | 74.6 | 133.6 | 390730 | 3995396 |
| **CQC7** | 7 | 7 | 6.94 | 6.2 | 97.0 | 345.2 | 49.8 | 76.4 | 145.1 | 390730 | 3995396 |
| **CQC8** | 5 | 6 | 4.90 | 12.3 | 39.9 | 013.2 | 45.8 | 75.7 | 18.7 | 388775 | 3995479 |
| **CQC9** | 4 | 6 | 3.96 | 11.1 | 69.9 | 006.8 | 45.1 | 78.8 | 40.8 | 388775 | 3995479 |
| **CQD1A*** | 5 | 8 | 4.64 | 24.0 | 11.1 | 319.6 | 62.7 | 58.4 | 191.0 | 388766 | 3995510 |
| **CQD1B#** | 7 | 8 | 6.74 | 12.8 | 23.2 | 058.2 | -15.0 | 20.1 | 10.0 | 388766 | 3995510 |
| **CQD2A** | 7 | 8 | 6.98 | 3.5 | 295.6 | 333.8 | 62.1 | 68.9 | 191.5 | 390773 | 3995520 |
| **CQD2B** | 7 | 8 | 6.98 | 3.8 | 250.9 | 350.1 | 53.8 | 81.7 | 155.9 | 390773 | 3995520 |
| **CQD3B** | 8 | 8 | 3.99 | 5.5 | 280.2 | 351.9 | 70.1 | 71.3 | 239.0 | 390800 | 3995544 |
| **CQD4A** | 5 | 6 | 4.99 | 3.5 | 483.4 | 346.7 | 58.8 | 79.1 | 187.4 | 390820 | 3995582 |
| **CQD5A** | 5 | 6 | 4.98 | 5.3 | 209.8 | 332.2 | 61.2 | 67.6 | 187.8 | 390819 | 3995610 |
| **CQD5B** | 8 | 8 | 7.90 | 6.8 | 67.6 | 345.5 | 60.6 | 77.4 | 194.3 | 390819 | 3995610 |
| **CQD6A** | 4 | 6 | 3.97 | 8.8 | 111.2 | 337.1 | 53.4 | 71.0 | 162.9 | 390823 | 3995628 |
| **CQE1** | reject | - | - | - | - | - | - | - | - | 391105 | 3995242 |
| **CQE2** | 6 | 6 | 5.87 | 10.9 | 38.8 | 314.1 | 60.2 | 54.1 | 185.8 | 390804 | 3995588 |
| **CQE3** | 4 | 5 | 3.99 | 6.1 | 230.1 | 347.2 | 50.2 | 77.9 | 141.4 | 390813 | 3995597 |
| **CQE4** | 4 | 6 | 3.98 | 7.6 | 145.9 | 310.7 | 52.6 | 50.1 | 175.0 | 390806 | 3995600 |
| **CQE5** | reject | - | - | - | - | - | - | - | - | 388736 | 3995748 |
| **CQE6** | 3 | 5 | 2.97 | 15.5 | 64.7 | 338.3 | 26.6 | 60.6 | 120.8 | 388610 | 3995150 |
| **CQE7** | 4 | 5 | 3.98 | 7.5 | 151.6 | 347.1 | 52.1 | 78.7 | 149.6 | 390608 | 3995095 |
| **CQE8** | reject | - | - | - | - | - | - | - | - | 388613 | 3995094 |
| **CQE9** | 6 | 7 | 5.85 | 11.9 | 32.9 | 102.6 | 71.8 | 23.3 | 289.5 | 388602 | 3995058 |
| **CQE10** | 3 | 6 | 2.98 | 13.1 | 89.9 | 106.3 | 19.4 | -7.0 | 326.1 | 388594 | 3995055 |
| **CQF1A** | 8 | 8 | 7.94 | 5.4 | 107.8 | 341.2 | 55.3 | 74.6 | 160.3 | 390711 | 3995335 |
| **CQF1C** | 4 | 6 | 3.93 | 10.8 | 41.3 | 322.6 | 40.8 | 55.8 | 152.6 | 390657 | 3995355 |
| **CQF2A** | reject | - | - | - | - | - | - | - | - | 388657 | 3995355 |
| **CQF2B*** | 4 | 6 | 3.82 | 23.1 | 16.8 | 305.8 | 60.6 | 48.1 | 188.4 | 388657 | 3995355 |
| **CQG1** | reject | - | - | - | - | - | - | - | - | 388593 | 3995033 |
| **CQG2** | reject | - | - | - | - | - | - | - | - | 388593 | 3995033 |
| **CQG3** | reject | - | - | - | - | - | - | - | - | 388593 | 3995033 |

EXPLANATION: Paleomagnetic data from the studied samples. Site is the sampling location; N is the number of samples used from the actual number of samples (No) collected at each site; R is the resultant vector length; $\alpha_{95}$ is the 95% confidence interval about the estimated mean direction, assuming a circular distribution; k is the best estimate of the Fisher precision parameter; Dec and Inc are the in situ declination and inclination; VGP Lat and Long are the latitude and longitude of the virtual geomagnetic pole for each site; UTM Northing and Easting are site coordinates (WGS84).
* in sampling location indicates site mean direction of high dispersion ($\alpha_{95}$ > 15°); # indicates site mean lies greater than 18° of the overall group mean direction.

and for less than 10% of the samples it was necessary to use the origin as an anchor. Magnetization vectors with maximum angular deviation values greater than 5 degrees were not included in site-mean calculations.

### *Petrography methods*

Thin sections of samples from selected sites were prepared for petrographic analysis to identify the minerals present, characterize the sample textures, assess the relation of the magnetic minerals with the silicate minerals, and, if possible, assess the petrogenetic history of the magma from which the samples solidified. Hand samples were collected in the field, cut into billets, and sent to High Mesa Petrographics, Los Alamos, NM for preparation into thin sections. The thin sections were viewed using a Meiji ML 9000 polarizing microscope.

## Results

### *Field observations and petrology*

The western edge of the Española Basin is located about 10 km northwest of the city of Española, NM. The Española Basin is characterized by many rift-related geologic structures including faults of varying styles and motion, rift-basin sediment fill, basaltic intrusions, lava flows, and Quaternary terrace surfaces (Koning et al., 2005). Magmatism in the Espanola Basin is related to the Jemez Mountain volcanism and is also associated with rifting. Backbone-like dikes intruding the light-colored Ojo Caliente Sandstone of the Tesuque Formation (Santa Fe Group) are exposed throughout the study area. The studied dikes are tabular, fine grained, and mafic in composition (basalt). The dikes range from 0.5–3.5 m wide, form en echelon segments, and strike generally north-south. The minerals in the hand samples are 1.0–2.0 mm in length, often with elongated geometries, and include olivine (vitreous luster and olive-green color), plagioclase (white to gray tabular crystals), and minute augite (stubby prisms) phenocrysts. Many of the dikes have vesicles that may be filled with secondary calcite. At a few locations elongated vesicles and mineral lineations occur on the faces of the dikes.

### *Petrographic analyses*

Petrographic analysis of the Rio del Oso dike samples from localities CQ1, 2, and 7 reveal hypocrystalline textures consisting of 50% glass and 50% crystals. The glassy component occurs as brown-colored isotropic material that is intergranular to the framework silicate minerals. Major minerals include olivine (10%), Ca-plagioclase (bytownite) (30%), augite (5%), and magnetite (<5%). The mineralogy was confirmed with powder x-ray diffraction analysis (Trujillo, 2014). Plagioclase ranges from 1.0 to 5.0 mm in length and occurs as euhedral phenocrysts and lath-like matrix crystals, many of which display swallowtail form. Olivine and clinopyroxene range from 1.0 to 2.0 mm in size and are subhedral to anhedral intergranular crystals. Magnetite is present as <0.10 mm, equant, disseminated grains, and as elongate grains with a dendritic habit. The presence of glass, as well as the swallowtail morphology of plagioclase laths and dendritic habit of the Fe-Ti oxide phases indicate undercooling of the host magma, consistent with shallow emplacement and rapid cooling (Lofgren 1983; Fig. 5). The mineralogy of the samples, along with their age and geographic location, supports their association with the Lobato Formation basalt flows. Thus, the mineral composition of the studied dikes is similar to that of Lobato basalt. Differences between individual flows and sampled intrusions include textural characteristics, including varying sizes of the phenocrysts, which can be attributed to the manner in which they cooled.

### *Paleomagnetic results*

#### General demagnetization behavior

Fifty-seven sampling sites were established, with 48 sites yielding interpretable results. Additional samples from six of the sites are not used to calculate the group mean direction (Table 2). The nine uninterpretable sites did not yield stable end-point demagnetization behavior, and the six other sites yielded high dispersion between samples from the same site. We attribute these behaviors to either the rocks being struck by lightning, or chemically altered; samples from these fifteen sites are therefore excluded and our interpretation of the deformation in the region is based on forty-two sampling sites.

The majority of the samples were fully demagnetized with a combination of alternating field and thermal demagnetization treatments. Magnetization directions are well-grouped at the site level, with most sites yielding a single-component of magnetization that decays to the origin with less than ten percent of the NRM remaining after treatment in an alternating field of up to 20 mT and/or thermal treatment up to 525°C (Fig. 4). The majority of the samples contain a single characteristic remanent magnetization (ChRM), although some samples contain more than one magnetization component, which is randomized by about 300°C. We interpret these magnetizations as viscous remanent magnetization (VRM) overprints. After the VRM is removed, the remaining magnetization is likely a primary thermoremanent magnetization (TRM); which we interpret as the ChRM.

Paleomagnetic results from the forty-two sampling sites yield a group mean of D=344.0°, I=51.1°, $\alpha_{95}$= 6.1°, k=14.1 (see Table 2 notes for an explanation of these parameters). The group-mean result is discordant to the <10 Ma pole direction of D=356.0°, I=54.4°, $A_{95}$=3.3° (Fig. 6; Table 3), with an inferred counterclockwise rotation of -12.0° ± 7.2, and a flattening of +13.3° ± 5.5° (Demarest, 1983; Beck, 1989).

To test the dispersion of the site-mean virtual geomagnetic poles (VGPs), we compared the average VGP dispersion to the predicated dispersion value for the latitude of the site (36.08° N) (Merrill and McElhinny, 1983). If secular variation has been adequately sampled, the observed angular dispersion estimate of site-mean VGPs should be consistent with the predicted value. The expected dispersion ranges from 13.5° to 17.7° (average = 15.6° ± 2.1°) (Table 2; Merrill and McElhinny, 1983; Cromwell et al., 2018). The estimated dispersion (S) of the forty-two site-mean

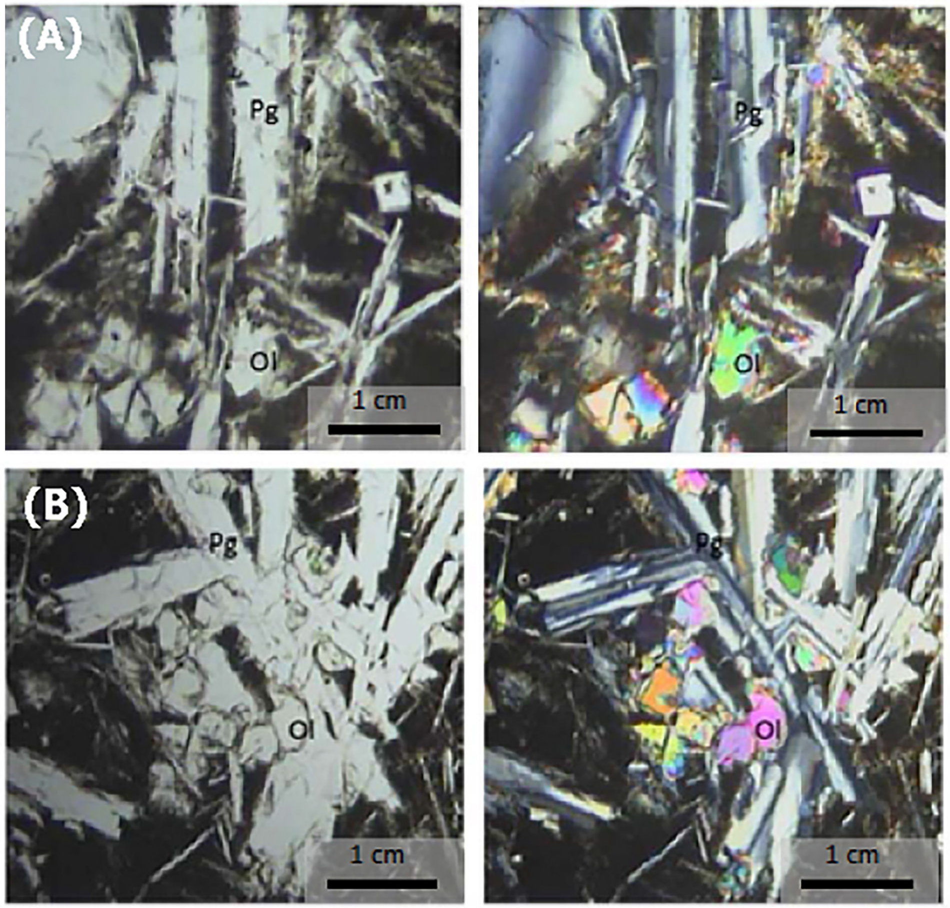


Figure 5. Representative photomicrographs of samples from the Rio del Oso dike swarm. The images on the left are in plane-polarized light and the images on the right are in cross-polarized light. (A) sample CQ3, (B) sample CQ4. The rocks display a hypocrystalline and olivine porphyritic texture. Minerals include olivine (Ol, high relief and high birefringence), plagioclase feldspar (Pg, lath shapes), and Fe-Ti oxide (elongate to dendritic shape, opaque). Interstitial glass is brown and isotropic.

directions yields a group-mean VGP dispersion of 24.4° ± 7.0° (95% confidence), a value that is statistically within the predicted VGP dispersion estimate. From this analysis, we suggest that paleomagnetic results from the forty-two sites may reflect either 1) a time interval covering a relatively long period of secular variation, or 2) tectonic deformation associated with rotation. As we discuss below, we prefer the latter interpretation of the data, given the field relationships.

**Stability of the magnetization—contact test results**

A contact test compares remanence directions in an igneous rock, the baked zone adjacent to the intrusion, and the unbaked zone away from the thermal aureole associated with the intrusion. An igneous intrusion heats the surrounding host rock and as both the magma and adjacent rock cool in Earth's magnetic field, the materials acquire a remanent magnetization that reflects the ambient field direction at the time of emplacement of the intrusion. The host rock often acquires a new remanence (i.e., remagnetization) in the same direction as the intrusion within a few centimeters to meters of the contact (Fig. 7). In general, if samples are taken from the intrusion and from the surrounding contact zone, and they yield the same magnetization direction, then the rocks from the intrusion are likely to carry a viable paleomagnetic direction (Everitt and Clegg, 1962; Calderone and Butler, 1984). Since the country rock and the igneous intrusion are generally very different rock types, agreement between the direction of magnetization of the intrusion and that of the baked region of the country rock provides strong evidence for the stability of the magnetization of the intrusion. The contact test compares remanence directions from the intrusion, the baked zone, and the unbaked zone (Fig. 7). In this study the host rock (Ojo Caliente Sandstone Member of Galusha and Blick, 1971), was sampled for a distance of 20 meters from the dike contact at intervals of about 1–2 m (Fig. 7), with a total of eight samples collected in the host rock, eight samples in the baked zone, and eight samples in the dike. The mean paleomagnetic direction from the host rock (sample CQB2) is D=225°, Inc=33°, the baked zone (CQB3) D=329°, I=30°, and the dike (CQB4) D=332°, I=44° (Fig. 7). Thus, paleomagnetic directions in sites located closer to the contact with the dike are similar to those of the intrusion, and we conclude that the results from the test are positive and that the remanence of the dike is a primary ChRM.

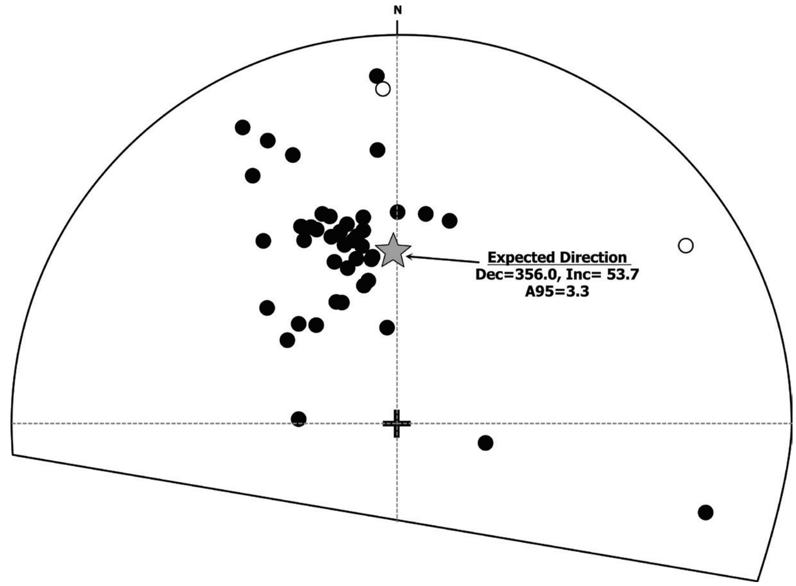


Figure 6. Paleomagnetic data from the sites that yielded interpretable results. Equal area lower hemisphere projection of all accepted site-mean directions. The excluded data were of high dispersion and are not shown. The open circles are reverse polarity sites. Gray star represents the <10 Ma field direction.

Table 3. Selected paleomagnetic poles for North America and corresponding expected directions.

| Age (Ma) | λ (N°) | Φ (E°) | $A_{95}$ | K | Expected Direction Dec | Inc | $A_{95}$ | Reference | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **0** | 90.0 | 180.0 | - | - | 360.0 | 55.5 | - | a | GAD |
| **15.9-11.6** | 88.3 | 209.0 | 6.3 | N/A | 358.3 | 56.7 | 5.1 | b | Steens Mountain Basalts |
| **15.9-11.6** | 88.7 | 171.6 | 4.0 | N/A | 358.4 | 55.7 | 3.3 | b | Columbia River Basalts |
| ***<10** | 86.5 | 114.7 | 3.9 | N/A | 356.0 | 54.4 | 3.3 | c | <10 Ma Poles |
| **20** | 85.9 | 151.1 | 3.6 | N/A | 355.1 | 54.6 | 3.0 | d | 20 Ma mean pole |
| **23** | 76.2 | 210.0 | 7.4 | N/A | 346.4 | 63.7 | 8.6 | e | Colorado, Lake City Caldera[d] |
| **0** | 86.5 | 180.7 | 3.0 | 96.2 | 355.8 | 56.5 | 2.4 | f | 20 Myr sliding window every 10 Myr |
| **5** | 86.1 | 174.8 | 2.6 | 105.2 | 355.2 | 56.2 | 2.1 | f | " |
| **10** | 84.6 | 164.4 | 3.1 | 107.7 | 353.3 | 55.4 | 2.6 | f | " |
| **15** | 83.6 | 163.0 | 3.2 | 84.2 | 352.1 | 55.2 | 2.7 | f | " |
| **20** | 81.0 | 156.2 | 4.5 | 68.3 | 349.2 | 53.9 | 3.8 | f | " |
| **0** | 86.1 | 174.8 | 2.6 | 105.2 | 355.2 | 56.2 | 2.1 | f | 10 Myr sliding window every 5 Myr |
| **10** | 85.0 | 168.1 | 2.0 | 94.2 | 353.8 | 55.8 | 1.6 | f | " |
| **20** | 83.3 | 164.2 | 2.7 | 75.6 | 351.7 | 55.3 | 2.2 | f | " |

EXPLANATION: Age (Ma) is the age range or age of the paleomagnetic pole; λ (N°) and Φ (E°) are latitude and longitude of the paleomagnetic reference pole; $A_{95}$ is the semi-angle of the cone of 95% confidence about the pole; K is the best estimate of the precision parameter of the pole (Fisher, 1953) (N/A, not available); Expected Direction Dec & Inc are expected declination and inclination of the reference directions as calculated for the latitude and longitude of the Rio del Oso intrusions (36.08° N, 106.22° W); $A_{95}$ is the estimated semi-angle of the cone of 95% confidence about the reference directions. Sources: a, pole and expected direction based on the hypothesis of a time-averaged geocentric axial dipole (GAD); b, Mankinen et al., 1987; c, Brown and Golombek (1985) mean of <10 Ma poles compiled by Irving and Irving (1982) (poles 1 through 12, with the exception of pole 5 from the Servilleta basalt flows north of the Española Basin and pole 9 from the Chamita Formation); d, Harrison and Lindh (1982), e, Colorado, Lake City Caldera; f, Besse and Courtillot (2002), synthetic North American poles.
*Our rotation estimates from the (CQ) Chili quadrangle basaltic dikes is based on the <10 Ma pole (highlighted red) calculated by Brown and Golombek (1985).

## Rock magnetic experiment results

Rock magnetic experiments were conducted to determine the magnetic mineralogy and domain state of the principle magnetization carriers in the Lobato Formation intrusions. The results of the experiments indicate that the dominant magnetic mineral phase is a cubic Fe-Ti oxide of a restricted magnetic grain size, primarily pseudo-single domain titanomagnetite with a minor amount of coarse-grained maghemite or pyrrhotite.

## Curie point estimates

Continuous susceptibility versus temperature results yield Curie-point estimates that range from ~100°C to 560°C. These temperatures are consistent with the presence of a range of moderate- to low-Ti composition magnetite with the presence of an iron sulfide phase (pyrrhotite) in some samples (Fig. 8). In sample CQ2 the heating and cooling curves vary widely, which indicates that there is a wide Curie-temperature decrease that is probably a result of the creation of new magnetite as a result of heating. Another possible explanation for the large variations between the heating and cooling curves is chemical alteration. These data provide evidence that the samples contain a magnetic phase that is capable of preserving a geologically stable magnetic phase that preserves a primary remanent magnetization.

## IRM and BIRM experiment results

All Isothermal Remanent Magnetization (IRM) acquisition curves are steep

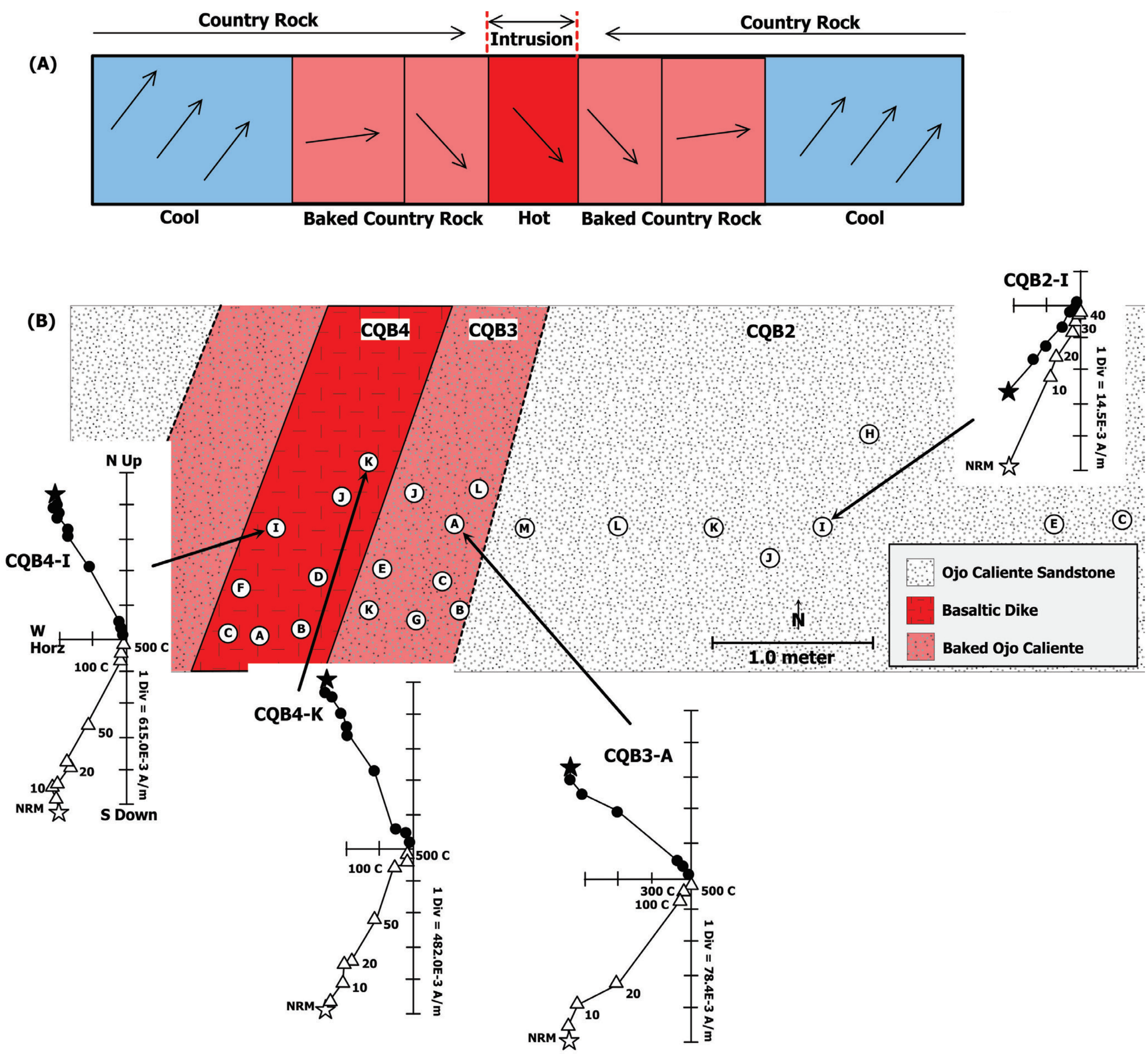


Figure 7. Contact test results. (A) Schematic diagram depicting a baked contact test that yields positive results. Emplacement of the intrusion (red) heats the country rock (blue), resulting in remagnetization. Near the intrusion the country rock yields a magnetization direction similar to that of the intrusion; farther from the intrusion the rocks are only partially reset. The arrows schematically represent differences in magnetic field direction. (B) Simplified illustration of one of the studied intrusions (CQB4) and its adjacent baked zone. The circled letters represent sample drill sites. The demagnetization diagrams show the behavior of selected samples during progressive alternating field and thermal demagnetization experiments.

and reach ~90% saturation by ~0.40 T, with the remaining 10% of the magnetization acquired up to 0.60 T (Fig. 9A). Backfield IRM curves yield coercivity of remanence values between 0.04–0.05 T, which is also consistent with a low Ti magnetite phase (Fig. 9B). The results indicate a dominance of magnetite, likely single domain titanomagnetite of a restricted grain size, along with the presence of titanomaghemite and likely pyrrhotite; we see no evidence of hematite (Özdemir and Dunlop, 1993). These data support the Curie point estimates in that the rocks contain a magnetic phase capable of preserving a stable remanence.

## Discussion

### *Angular standard deviation of the virtual geomagnetic poles (VGPs)*

Observed paleomagnetic declinations that are discordant, when inclinations are essentially identical to some expected value, can provide vertical axis rotation estimates for parts of the crust in either an absolute or a relative framework. Absolute rotation determinations require results that adequately sample the geomagnetic field over a sufficiently long time, which are then compared with a robust estimate of the time-averaged field based on independent paleomagnetic data (paleomagnetic poles) from the respective craton. Relative determinations, on the other hand, require sampling a single, laterally extensive datum (e.g., Wells and Hillhouse, 1989; Byrd et al., 1994; Sussman et al., 2006) located in several different structural settings (e.g., a regionally extensive ash-flow tuff). Under ideal circumstances, where either a time-averaged geomagnetic field is well-sampled, or a single datum consistently yields a very high-precision result, estimates of absolute vertical axis rotation typically have 95% confidence limits of ~4° to 10°, and relative vertical axis rotation estimates typically have confidence limits less than 5°. The paleomagnetic data from the Rio del Oso dike swarm allow for an estimate of absolute rotations relative to an adequately sampled geomagnetic field over a sufficiently long time, assuming they have adequately averaged secular variation of Earth's magnetic field.

As noted above, the expected dispersion of the VGPs for the latitude of north-central New Mexico during the mid to late Miocene ranges from 13.5° to 17.7° (average = 15.6° +/- 2.1°) (Table 2; Merrill and McElhinny, 1983; Cromwell et al., 2018). The angular standard deviation of magnetic poles obtained from the Rio del Oso dikes is 24.4° +/- 7.0° (95% confidence); a value which is statistically within the predicted VGP dispersion estimate, but greater than would be expected using paleosecular variation model G of McElhinny and McFadden (1997), which is based on VGP scatter during the past 5 Ma. Model G values are strictly valid only for VGPs derived from lava flows. Lava flows are erupted instantaneously relative to paleosecular variation and provide spot readings of the geomagnetic field at the time of eruption. Arguably, Model G dispersion estimates may not be appropriate when applied to slowly cooled intrusive rocks. Estimates of angular standard deviation

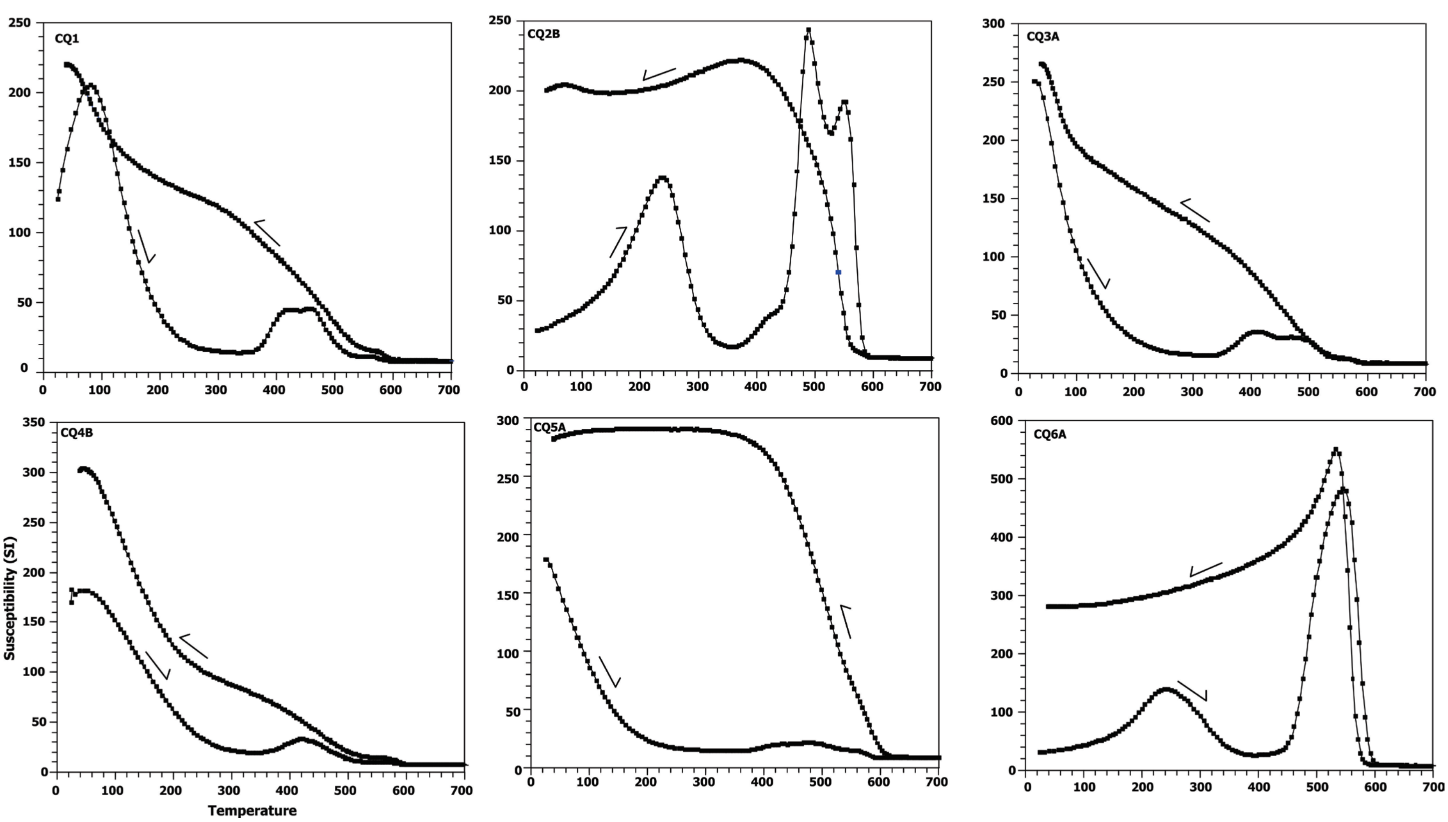


Figure 8. Continuous low-field susceptibility versus temperature experiments. Curie point estimates range from ~100 to 560 °C. These results indicate a range of moderate to low Ti- titanomagnetite compositions, and evidence of an Fe-sulfide phase (pyrrhotite).

from intrusive 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). However, using estimates of angular standard deviation alone to assess the viability of a data set from tectonically complicated areas should be viewed with caution. Complications such as faulting, inability to correct for unrecognized tilting, and other tectonic issues may lead to estimates of angular standard deviation that seem large, thus leading to erroneous inferences regarding the reliability or quality of the data.

In order to make an argument for tectonic deformation, a critical benchmark for a paleomagnetic data set is whether it has adequately averaged secular variation. A standard test is to compare observed dispersion of site-mean VGPs with the predicted dispersion (Merrill and McElhinny, 1983; Cromwell et al., 2018). If secular variation has been adequately sampled, the observed angular dispersion of site-mean VGPs should be consistent with that predicted for the paleolatitude of the sampling sites. If the observed dispersion of site-mean VGPs is less than predicted, a likely explanation is that the group mean represents a population of site mean directions that did not sample a time interval covering the periodicities of secular variation (≤ $10^5$ yrs). The opposite situation is presented by a VGP dispersion that is substantially greater than predicted. In this case, it is probable that there is a source of VGP dispersion beyond secular variation. Often, a high dispersion can be explained by a tectonic disturbance within the sampling region, or there is difficulty in determining the site-mean ChRM directions. The latter is unlikely for our study of the Rio del Oso dike swarm because the demagnetization behavior is relatively straightforward (Fig. 4). We argue that the higher than predicted value likely represents a tectonic disturbance, although these conclusions should be viewed with a certain level of caution. For the interval from 5 Ma to 45 Ma, the amplitude of VGP dispersion in all latitude bands is greater than that for the 0 Ma to 5 Ma

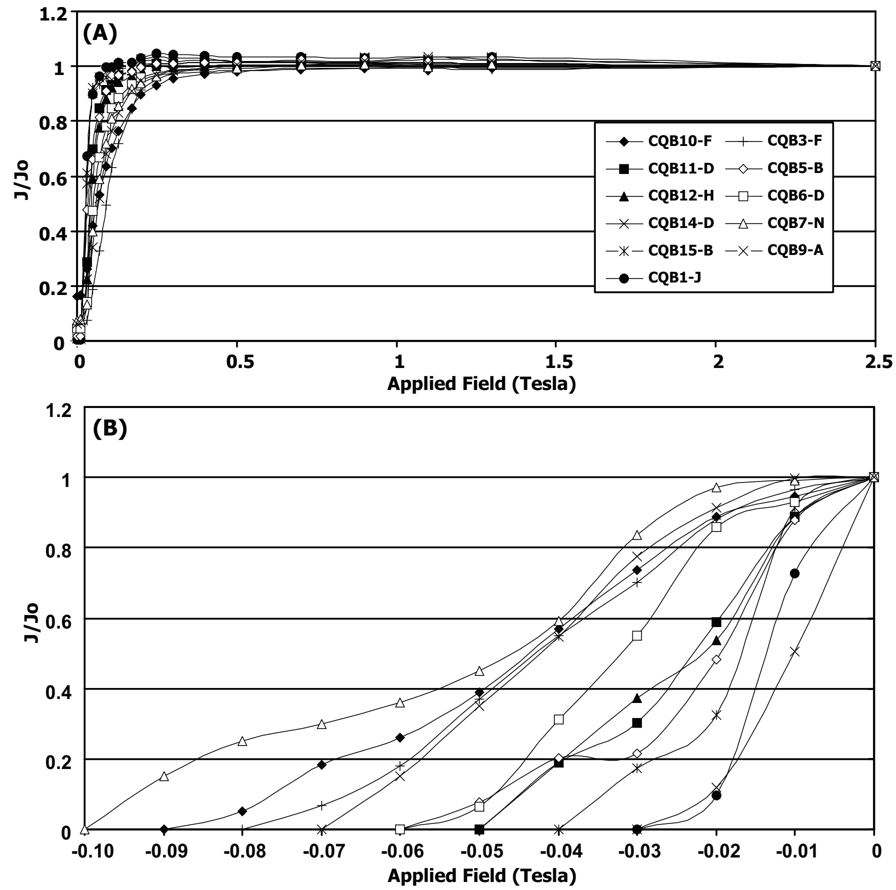


Figure 9. Isothermal remanent magnetization (IRM) and back-field IRM experiments. (A) Normalized isothermal remanent magnetization (IRM) from representative samples. The steep acquisition and saturation by ~0.4 T is indicative of titanomagnetite of a restricted single domain to pseudo-single-domain grain size. (B) Normalized back-field isothermal remanent magnetization acquisition demagnetization curves from representative samples. Coercivity of remanence values are typical of titanomagnetite with a low-Ti composition.

interval cited above. For example, in the band of latitude centered on 10° N, VGP dispersion is ~19° for 5 to 45 Ma and ~13° for 0 to 5 Ma. This may also be a factor to explain the higher than predicated value observed in our data set from the Rio de Oso dike swarm.

## Vertical axis rotation in the Rio Grande Rift

Rocks located at or near the surface of the Earth generally behave in a brittle manner when deformed under moderate strain rates. The Earth's crust deforms by distortion, displacement, and rigid-body rotation. In the case of rigid-body rotations, vertical axis rotations are often difficult to identify based on macro- and micro-structural analysis. The application of paleomagnetism, however, has proven to be a reliable technique for quantifying vertical axis rotation directions and magnitudes. Many paleomagnetic studies have been conducted to identify vertical axis rotations, or lack thereof, associated with regional and localized faulting (e.g., Gillett and Van Alstine, 1982; Ron et al., 1984; Hudson and Geissman, 1987, 1991; Janecke et al., 1991; Hudson, 1992; Cashman and Fontaine, 2000; Hudson et al., 1994; Wawrzyniec et al., 2002; Petronis et al., 2002, 2007). Several workers have conducted studies in the Española Basin and have implemented the use of paleomagnetic analysis to assess whether or not vertical axis rotation has in fact taken place within the region (Brown and Golombek 1985, 1986; Salyards et al., 1994; Hudson et al., 2004). The Española Basin block is bounded by a series of accommodation structures. These include the Tijeras-Cañoncito fault zone to the south, the Pajarito fault zone to the west, and the Embudo fault zone to the north (Kelley, 1977; Muehlberger, 1979; Brown and Golombek, 1986). A kinematic model of block rotation in the Española Basin was developed by Muehlberger (1979), advanced by Brown and Golombek (1986), and further supported by Harlan and Geissman (2009). The model was in part developed based on the results from several paleomagnetic data sets from across the Española Basin, all of which yield internally as well as spatially consistent results. Previous data sets indicate that vertical axis rotation amounts vary significantly from the western margin of the basin to the eastern margin of the basin. A compilation of all the data along the western margin of the Española Basin indicates that the block rotation direction is dominantly counterclockwise with a domain near the western basin margin showing a component of clockwise rotation (Fig. 10A). This observation arguably reflects heterogeneous strain accommodation across the basin. This further suggests that movement along the western margin has been greater than it is on the eastern margin of the Española Basin (Salyards et al., 1994). Alternatively, Sussman et al. (2011) conducted a study of the Bandelier Tuff within the Española Basin block to assess possible components of vertical axis rotation within the basin. The results of the study were interpreted to indicate that no vertical axis rotations occurred during Quaternary time. It was concluded by Sussman et al. (2011) that vertical axis rotation along the western Española Basin block was not associated with regional deformation, but rather attributed to localized deformation events.

### Vertical axis rotation in the Española Basin

The group mean result from forty-two paleomagnetic sites established in the Rio del Oso dike swarm record a modest, yet statistically significant component of counter-clockwise rotation relative to the average <10 Ma pole direction, with an inferred rotation of -12.0° ± 7.2° and flattening of +13.3° ± 5.5°. As noted above, this is an absolute rotation estimate relative to the selected <10 Ma pole (Table 3). The sampling sites are distributed over a 4.8 km$^2$ area and it is probable that the group mean direction may not be representative of along-strike and spatially variable vertical axis rotations across the area. Based on the dispersion of the paleomagnetic data, some sites record greater or less than the amount of vertical axis rotation based on the collective group mean direction. Numerous small-scale synthetic and antithetic faults crosscut the sampling area and may have facilitated differential vertical-axis rotation in the area.

Estimates from previous studies (Brown and Golombek 1985, 1986; Salyards et al., 1994; Hudson et al., 2004) indicate tectonic rotation values and directions similar to those reported here. In addition, other geologic data (Kelley 1977, 1979) suggest that block rotations are likely taking place. Paleomagnetic results from this study indicate that the western margin of the Española Basin has experienced a modest magnitude -12.0° ± 7.2° counter-clockwise rotation about the vertical axis. The rotation is ascribed to post-middle Miocene regional extension. The model proposed by many workers to explain counter-clockwise vertical axis rotations is depicted in Figure 10B. Within the Española Basin, and more locally within the Chili Quadrangle, a complex array of faults are thought to transfer components of both dip-slip and strike-slip deformation across the region. There are two major faults in the region: the Cañada del Amagre and the Santa Clara fault systems. Movement along these structures and other minor faults associated with continental extension has likely facilitated rotation in this part of the Española Basin.

## Conclusions

The paleomagnetic data presented here provide evidence for a modest amount of counter-clockwise vertical-axis rotation along the western margin of the Española Basin. The rotation is likely associated with extension within the Rio Grande rift. The supporting rock-magnetic experiments and field tests indicate that the magnetization data are geologically stable and thus represent

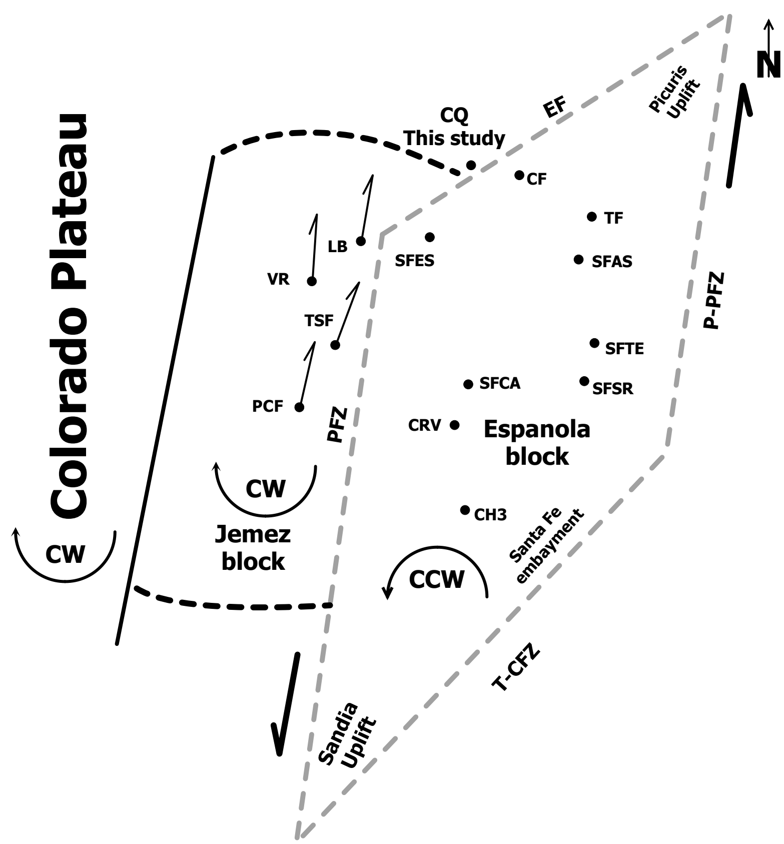


**Figure 10A.** Schematic model proposed by Brown and Golombek (1986) of the apparent rotations within the Jemez block and other site locations in the Española block (cf. Fig. 1). Deviation from geographic north in the Jemez block indicates an apparent vertical axis rotation; the lines deflected to the right indicate a clockwise (CW) rotation. Labels explained in Figure 10B caption.

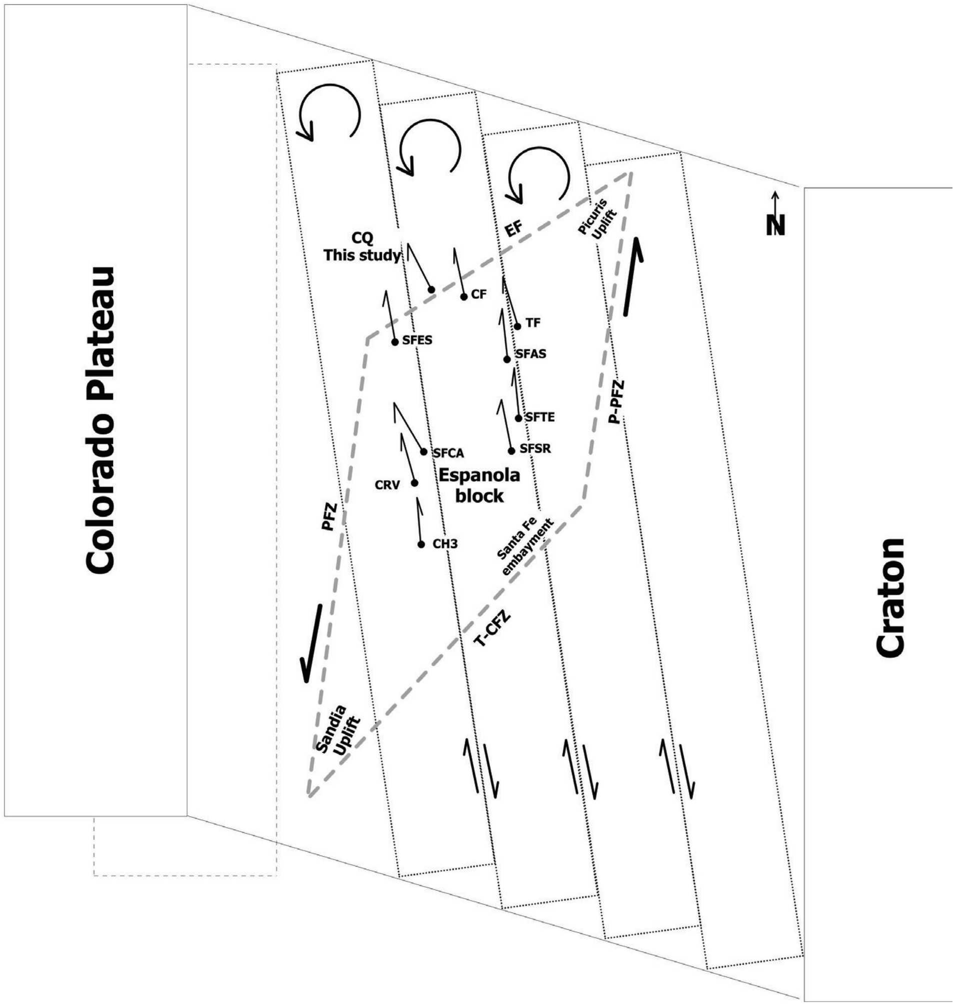


Figure 10B. Simplified model of inferred block rotations in the Española basin of the Rio Grande rift, based in part on paleomagnetic data from Muehlberger (1979), Barghoorn (1981), Brown and Golombek (1986), and Harlan and Geissman (2009). Deviation of the arrows from geographic north indicate apparent magnitude of rotation; thus lines to the left of north indicate counter-clockwise (CCW) rotation. The block model on which the inferred paleomagnetic rotations are shown is after Wawrzyniec et al. (2002) and schematically depicts how crustal blocks or sets of blocks may have rotated in a CCW sense during Neogene dextral transtension. The data from the Oso de Arroyo dike swarm are rotated counter-clockwise and are situated north of the concealed trace of the Embudo fault. This extends the domain(s) of counter-clockwise rotation to the north. Abbreviations: Sedimentary rock units—CF, Chamita Formation; TF, Tesuque Formation; SFTE, Tesuque Formation, Nambé Member; SFAS, Tesuque Formation, Skull Ridge Member; SFSR, Tesuque Formation, Nambé Member; SFES and SFCA, Chamita Formation. Igneous rock units—CRV, Cerros del Rio volcanics; CH3, Cerrillos Hills and Ortiz Mountains; CQ, Chili Quadrangle Lobato intrusions (this study); LB, Lobato basalt; PCF, Paliza Canyon Formation; TSF, Tschicoma Formation; VR, Valles rhyolite. Major faults—T-CFZ, Tijeras-Cañoncito fault zone; PFZ, Pajarito fault zone; EF, Embudo fault zone; P-PFZ, Picuris-Pecos fault zone.

primary TRMs. Petrology demonstrates that the dikes are similar along strike and represent the same magma source emplaced into the shallow crust during extension. Together these data provide insight regarding the tectonic evolution of the western margin of the Española Basin. Paleomagnetic data from rocks of various ages and types throughout the Española Basin yield consistent results indicating that counter-clockwise rotation accompanied Neogene to recent extension within the Rio Grande rift. Problems exist with the regional coverage of paleomagnetic data and with the averaging out of paleosecular variation. It is apparent, however, that the consistency between different studies supports counter-clockwise block rotation across this latitude of the rift. The Rio Grande rift continues to extend at a slow rate and these data strongly suggest that the rift continues to evolve. The western margin of the Española Basin has been influenced by greater rotations than the eastern margin of the basin, which suggests that the faults within the rift heavily influence the degree of rotation between the blocks. The interaction of the faults located within the rift are responsible for the intra-rift rotations that continue today.

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# Gallery of Geology

## The Pennsylvanian section at Bishop Cap, Doña Ana County, New Mexico

*Spencer G., Lucas,* New Mexico Museum of Natural History, 1801 Mountain Road NW, Albuquerque, NM 87104
*Karl Krainer,* Institute of Geology, University of Innsbruck, Innrain 52, Innsbruck A-6020 Austria

Located about 19 km (12 mi) southeast of Las Cruces in Doña Ana County, New Mexico, Bishop Cap is a rugged peak at the southern end of the Organ Mountains. At an elevation of 1,651 m (5,419 ft), Bishop Cap rises about 335 m (1,100 ft) above the alluvial fans at its base. The miter-shaped peak looks like a bishop's cap, hence the name. Bishop Cap is on a westward-tilted fault block between the Organ Mountains of New Mexico and the Franklin Mountains of West Texas. Its western side is a monocline-like flexure that dips to the west beneath Quaternary alluvial-fan deposits.

The oldest strata exposed at Bishop Cap are along the eastern base of the peak. They are Mississippian marine rocks capped by the Late Mississippian (Chesterian) Helms Formation. A limestone-dominated Pennsylvanian section about 256 m thick makes up most of Bishop Cap, and these strata rest with evident disconformity on olive-gray shale of the Helms Formation.

During the early 20th Century, fluorite was mined at Bishop Cap and in the surrounding hills, and published descriptions of the mining geology and stratigraphy first appeared in the 1920s (Seager, 1973, 1981). The lithostratigraphic nomenclature long applied to the Pennsylvanian strata at Bishop Cap has been that of Nelson (1940), names he introduced at Vinton Canyon in the northern Franklin Mountains to the south. Nelson (1940) coined the names (ascending order) La Tuna, Berino, and Bishop's Cap members of the Magdalena Formation. At Vinton Canyon, these strata and an overlying unnamed interval of Pennsylvanian strata comprise a stratigraphic section about 823 m thick (Harbour, 1972).

At Bishop Cap, Seager (1973, 1981) mapped the Pennsylvanian strata as the La Tuna and Berino formations of the Magdalena Group (ironically, Nelson's "Bishop's Cap Member" is not exposed at Bishop Cap, having been removed by

The Pennsylvanian stratigraphic section along the southeastern face of Bishop Cap. The slightly folded limestone in the foreground is the base of the Horquilla Formation ("La Tuna Formation," our unit A) disconformably overlying a shale slope at the top of the Upper Mississippian Helms Formation. Unit A extends up through the lower interval of cliff- and ledge-forming limestone. It is overlain by a slope-forming interval (base of "Berino Formation," our unit B), followed by a relatively thin cliff of limestone (unit C), another slope-forming interval (unit D) and then the limestones at the top of the peak (unit E).

erosion). We have measured the Pennsylvanian stratigraphic sections at Bishop Cap and in Vinton Canyon, and they are lithologically very similar to Pennsylvanian strata assigned to the Horquilla Formation to the west (especially in the Big Hatchet Mountains of Hidalgo County: Lucas et al., 2017) and to the northwest in the Robledo Mountains of Doña Ana County (Krainer et al., 2015). Therefore, we assign the Pennsylvanian section at Bishop Cap to the Horquilla Formation and note that Nelson's units La Tuna, Berino, and Bishop's Cap members may prove useful as local, member-level subdivisions of the Horquilla Formation (Krainer et al., 2020). More study is ongoing to resolve fully the lithostratigraphy and correlation of the Pennsylvanian strata in southern New Mexico and West Texas.

At Bishop Cap, we divide the Pennsylvanian section into five informal units (intervals), A–E. Unit A is the La Tuna Formation as mapped by Seager (1973, 1981). It is ~79 m thick and mostly limestone (79% of the unit thickness), much of it cherty (45% of the thickness). Covered intervals are shale and/or nodular limestone and make up about 20% of the unit thickness. There is a single sandstone bed (bed 20), about 1.1 m thick, with plant fossils of cordaites in it. Most of the limestone beds in unit A are 0.5–2 m thick, cherty and are as thick as 5.2 m. Mostly they are wackestones and feature silicified fossils of the demisponge *Chaetetes* (bed 2) and the coral *Petalaxis* (bed 24). The limestone beds that lack chert or have little chert are mostly crinoidal.

Unit B is ~84 m thick, and it is the lower part of the Berino Formation as mapped by Seager (1973, 1981). This is a slope-forming unit of relatively thick covered intervals (shale and/or nodular limestone) that are more than half (about 54%) of the unit thickness. These covered intervals are intercalated with relatively thin (mostly less than 1 m thick) beds of limestone that are wackestones and some packstones, some cherty and others lacking in chert. Notable are crinoidal packstones that are crossbedded, a bed with abundant fusulinids (bed 110) and a single, 0.5-m-thick bed of limestone-cobble conglomerate.

Unit C is a cliff-forming interval of limestone about 23 m thick. It consists almost entirely of chert-free crinoidal limestone in beds up to 4.2 m thick. Unit D is ~46 m thick and is another slope-forming interval similar to unit B. Thus, unit D is covered intervals (shale and/or nodular limestone) intercalated with thin beds (mostly less than 1 m thick) of crinoidal limestone. Unit E forms the top of Bishop Cap. It is ~20 m thick and is a cliff of limestone beds that are mostly cherty and nodular.

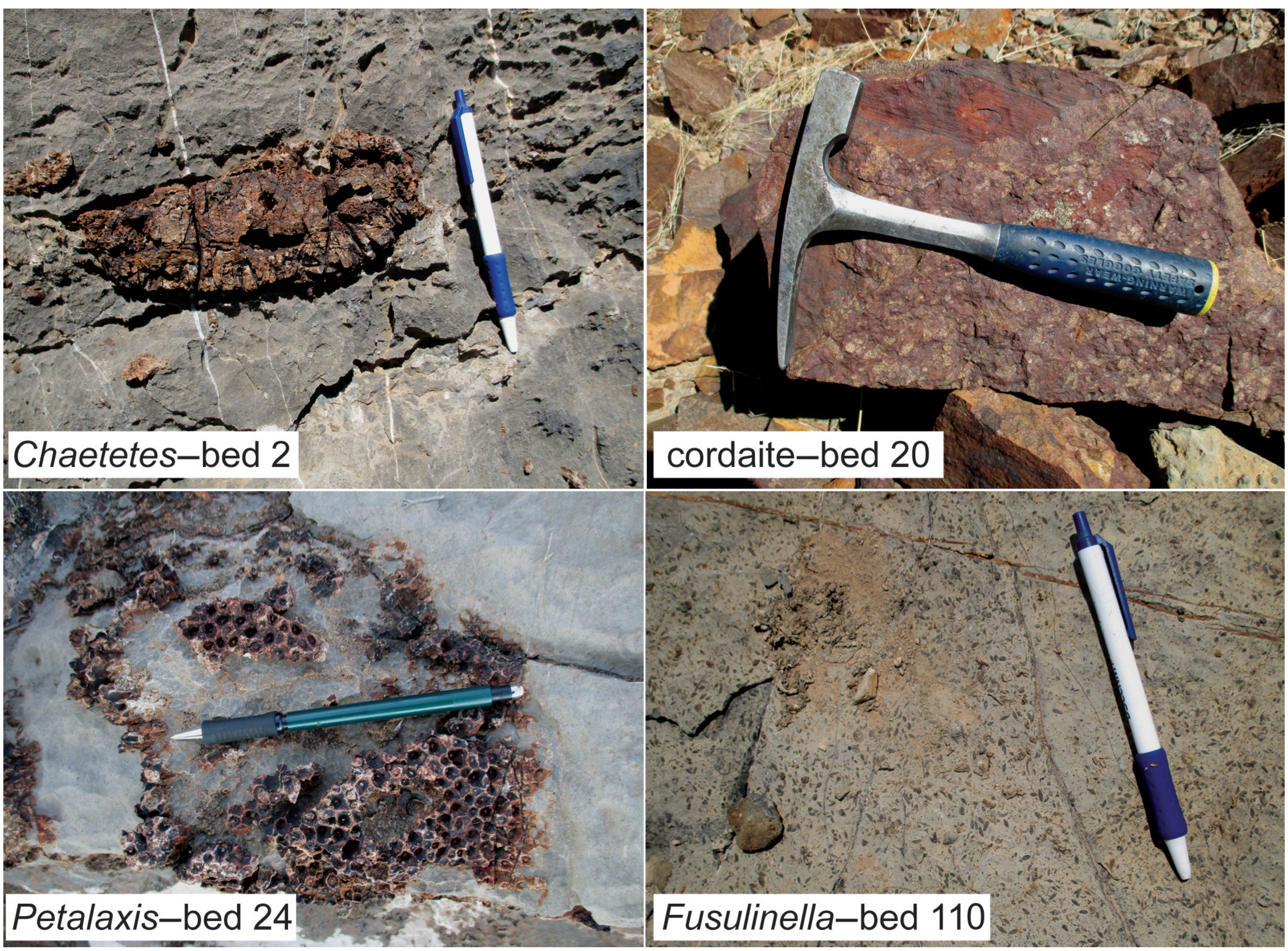


Photo 2. Some details of the Pennsylvanian section at Bishop Cap. Upper left, the silicified demisponge *Chatetes* in bed 2 of the section; upper right, cordaite plant fossil in bed 20; lower left, the coral *Petalaxis* in bed 24; lower right, bed of Atokan fusulinids, *Fusulinella* in bed 110.

Clopine (1992) documented fusulinids from a section he called Bishop Cap, though he actually sampled in the hills immediately north of the peak. Based on fusulinids, he assigned Morrowan, Atokan and early Desmoinesian ages to the section at Bishop Cap. Conodont biostratigraphy based on samples we collected and under study by James Barrick of Texas Tech University yield ages consistent with Clopine's fusulinid-based age assignments (Krainer et al., 2020). Thus, the conodonts indicate that the upper part of unit A (~65 m above base) is early Atokan, and the lowest Desmoinesian fauna occurs ~60 m above the base of unit B. Early Desmoinesian conodonts range through unit C and as least as high as the lower 10 m of unit D. Less age diagnostic Desmoinesian conodonts occur in the upper part of unit D and unit E. Further study of the microfossils from the Pennsylvanian strata at Bishop Cap is underway.

In the Horquilla Formation at Bishop Cap, thick-bedded to massive limestone is common in the lower part (units A and C), whereas nodular limestone is absent in unit A, rare in units B, C, and D and common in unit E. Chert is common in units A, B, and E and less common in units C and D. Muddy limestone types (wackestone, packstone, floatstone) containing a diverse fossil assemblage are common throughout the section, indicating deposition in a mostly low-energy, normal marine, open shelf to ramp setting with a slight increase in water depth toward the top (indicated by an increase in nodular limestone). The facies at Bishop Cap show some differences from the Horquilla Formation in the Robledo Mountains where nodular limestone is rare to absent (Krainer et al., 2015). In the Big Hatchet Mountains, the Horquilla Formation is much thicker (1,050 m), and nodular limestone is very rare to absent (Krainer et al., 2017). Thus, the Robledo and Big Hatchet sections of the Horquilla Formation were likely deposited in shallower water than the section at Bishop Cap. For a more detailed reconstruction of the depositional environments a microfacies analysis of the limestone facies is planned.

To understand the regional depositional setting of the Pennsylvanian strata at Bishop Cap, it is important to recognize that during the Early-Middle Pennsylvanian a seaway extended from southeastern Arizona/southwestern New Mexico (Pedregosa basin) across southernmost New Mexico (Orogrande basin, including the location of Bishop Cap) to the western end of the west Texas Delaware basin (e.g., Kues and Giles, 2004, figs. 5, 7, 8). Strata deposited in this seaway are mostly bedded limestones and shales that can locally form shallowing-upward cycles likely driven by glacio-eustasy (Lucas et al., 2017). These are strata of the Horquilla Formation to the west, grading eastward into strata in southern New Mexico long termed Magdalena Group (Formation or Limestone). We assign these strata in southern New Mexico to the Horquilla Formation. They were deposited in what we call the Horquilla seaway, an epicontinental sea that was located along part of the southwestern edge of equatorial Pangea during the Pennsylvanian-early Permian.

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# Ron Broadhead: Petroleum geologist extraordinaire

*—By Kristin Pearthree*

When Ron Broadhead was a child, he lived in a house in Danville, Illinois with hard shale rock flooring. A fitting precursor of things to come.

As a graduate student at the University of Cincinnati, he would study shale rocks containing hydrocarbon resources in northern Ohio. And thirty years later, when horizontal fracturing made possible the extraction of unconventional gas resources from shale rocks, he would again return to the subject as a petroleum geologist at the New Mexico Bureau of Geology and Mineral Resources. In March 2020, Ron retired from the Bureau of Geology and gained emeritus status, all while sporting his signature hat.

Ron was born in Racine, Wisconsin in 1955 on the western shore of Lake Michigan. His family moved through a few Midwestern states before settling in Illinois. His parents tried to interest him in many things to see what stuck. They even gave him a paleontology kit one year for Christmas.

While in his senior year of high school, he elected to take a semester of earth science and a semester of geography, both courses his councilor assured him were for "the students who could not pass any other kind of science." But he took them anyway. Through these courses, he developed a keen interest in the earth sciences.

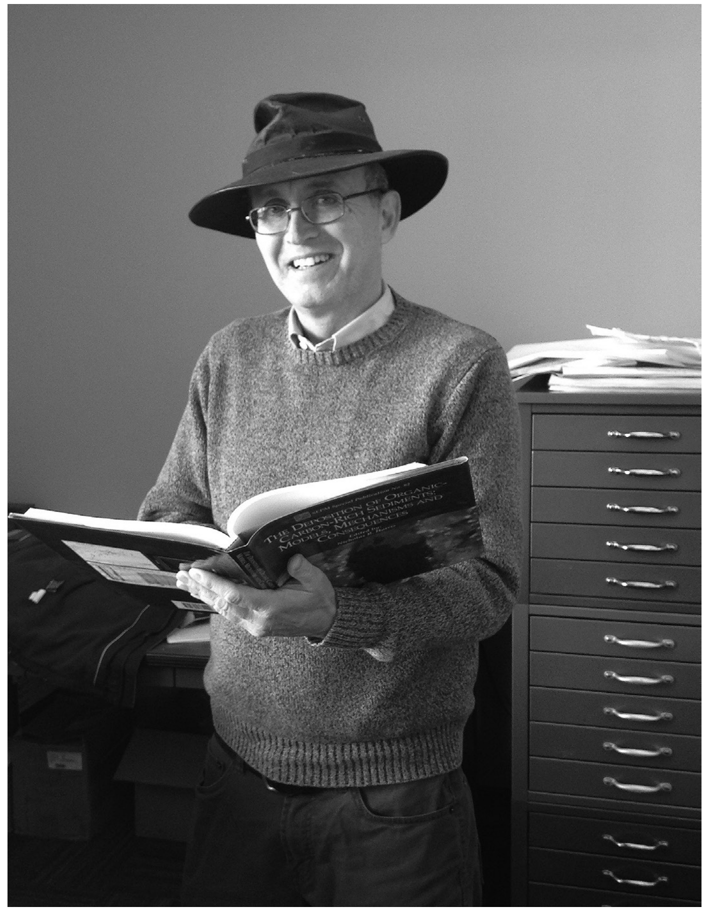
His high school had a room with filing cabinets full of literature from potential colleges. Ron found the postcard for New Mexico Tech and mailed it to request more information. He received a glossy brochure in return. When he showed New Mexico Tech's earth science curriculum to his teacher, she said it looked good. Ron decided to move from the rainy prairies of Illinois to the dusty town of Socorro, New Mexico in 1973.

He dove right into challenging classes that, "kept him out of trouble," or so he says. Ron was introduced to his future employer, then called the New Mexico Bureau of Mines and Mineral Resources, during the summer of his junior year.

Ron had just completed a geologist rite of passage: field camp. The professor teaching the class asked him if he would like to have a job for the rest of the summer working on a joint project led by the professor and the petroleum geologist at the Bureau. Ron then spent the rest of the summer examining metamorphic and igneous rocks in thin section. In the fall of his senior year, the petroleum geologist, Sam Thompson, offered Ron a job working on a project examining and logging well core cuttings. The end result was a junior authorship on a publication.

From there, global events shaped Ron's path into petroleum geology. When looking at graduate school options, Ron thought, "Where can I make a living?" The answer: petroleum geology.

In 1973, the Organization of Petroleum Exporting Countries (OPEC) issued an oil embargo on the United States in response to the U.S.'s decision to supply the Israeli military during the Arab–Israeli War. The embargo banned petroleum exports to the U.S. and introduced cuts in oil production. There were nationwide oil shortages and the price of oil skyrocketed. This spurred domestic oil exploration and production, ensuring job opportunities in the industry.



Ron in his office with his signature hat. Photo courtesy of Ron Broadhead.

So, for his graduate research at the University of Cincinnati, Ron studied approximately 400 million-year-old Upper Devonian gas shales in northern Ohio along Lake Erie. The study of gas shales was a very new field of study at the time, but one that would become essential in the future. Using stratigraphy, petrology, organic geochemistry, cores and rock outcrop studies, Ron conducted an integrated stratigraphic analysis of the shale rocks, and then related his results to where drillers had encountered natural gas.

Conventional oil production targets concentrated pockets of oil and gas in the subsurface with vertical drilling. In shale rocks, oil and natural gas are distributed within the formation and extraction by conventional means is not economically feasible. Technological developments in industry would later open up these "unconventional" resources. "People

Ron (right) on a core logging expedition with fellow University of Cincinnati graduate student Greg Hinterlong, December, 1978.
Photo by Roy C. Kepferle. Courtesy of Ron Broadhead.

asked me at the time, 'Why are you looking at shales?'" Ron remembers, "Now we know."

When Ron graduated in 1979, the only real jobs available for him were in the oil industry. He joined Cities Service Company working as a petroleum geologist in Oklahoma for two years. He went out to wells during the drilling process to verify if they should be completed or abandoned, developed drilling prospects in Oklahoma, Arkansas and Texas, and evaluated lease requests by other companies to drill on his company's land. "I learned a lot. It was a lot of responsibility for somebody that young but I think I did pretty well. I made a couple of mistakes but I was determined not to repeat them," says Ron. A lesson anyone can relate to.

But then one night, Ron returned to his apartment late after sitting on a well that was being drilled. He went into his kitchen. He had thrown out his copy of the American Association of Petroleum Geologists (AAPG) Explorer magazine and sticking out of the waste basket was a page with an advertisement for a petroleum geologist position at the New Mexico Bureau of Mines and Mineral Resources. Ron was tired. He thought, "Why not apply for it?" A month or two later, the Bureau called and asked him to come in for an interview.

And so Ron returned to Socorro in 1981. "I think I hit the ground running. The first day…the director at the time, Frank Kottlowski, came into my office and gave me a couple of assignments, so I took off with them," Ron remembers. Over the next 38 years, Ron became "Mr. New Mexico, when it comes to resources," according to Emeritus Oklahoma State University Professor Dr. John Shelton.

Ron conducted a pioneering study in the late 1980s on the Tucumcari Basin in the east-central part of the state. The basin was not a productive oil and gas province at the time. Using a number of fundamental geologic methods, Ron pieced together the basin's subsurface structure and stratigraphy. He then looked at how the structure influenced the location of source rocks, which produce oil and gas, versus reservoir rocks, where hydrocarbons become trapped. Reservoir rocks are targets for oil and gas exploration, and of keen interest to industry.

He returned again to the Tucumcari Basin in the early 2000s following a grant from the New Mexico State Land Office. By then hydraulic fracturing combined with horizontal drilling, a process commonly referred to as fracking, had changed the face of oil and gas exploration.

Hydraulic fracturing involves injecting a fluid usually mixed with sand into a target rock formation in the subsurface. The high pressure of the fluid injection generates fractures within the rock that are then held open by the sand. This increases connectivity in the rocks, allowing oil and gas to flow together through a spider web of fractures, becoming more concentrated and thereby increasing the ease of extraction.

In horizontal drilling, a well begins as a traditionally vertically-drilled well at shallow depths. Then, the well veers to a horizontal orientation when approaching the depth of the target rock formation. The horizontal orientation of the well ensures it intersects as many of the newly-formed fractures as possible. Hydraulic fracturing and horizontal drilling opened the door to "unconventional" oil and gas resources, like those present in the Tucumcari Basin and in the gas shales Ron studied as a graduate student.

"When I published the results of the grant, industry activity went wild and companies started leasing all over the place, including on state trust lands," says Ron.

Later in his career, Ron began working in the San Juan Basin in northern New Mexico, studying the Mancos Shale. Industry was just starting to take notice of the Mancos as a target formation for unconventional oil and gas extraction. As the Bureau's petroleum geologist, Ron was in a unique position to develop a basin-wide overview by mapping the potential distribution of resources.

One of Ron's most significant contributions to geoscience, however, comes from his investigations of the geology of helium resources. Helium gas is indispensable in modern society. It is used to cool the magnets in MRI machines, to make fiber optic cables and computer screens, and in mass production of computer chips. "And it makes you talk funny," Ron chuckles. Helium co-occurs with other natural gases, but not often in high enough concentrations to justify the expense required to extract it.

Ron mapped concentrations of helium-rich gases throughout the state. With helium resources becoming increasingly scarce, New Mexico stands to benefit from Ron's work. "[It's] still an up and coming resource," says Ron, "And nobody had done that [mapped statewide helium concentrations] before in any state." In helium, as in gas shales, Ron was ahead of the curve. Ron intends to continue investigating the geology of helium resources in his emeritus

Ron logging cuttings in the old Bureau of Geology building in 2000. Courtesy of Ron Broadhead.

position at his new office on the third floor of the Bureau of Geology's building.

Ron may be known for his wide-ranging knowledge of resources in New Mexico, but his work extends beyond just research and into teaching and professional service.

Ron taught Petroleum and Subsurface Geology at New Mexico Tech for 32 years, educating as many as 400 to 500 students. When he began teaching, he found that sometimes there was not any published literature that he could assign to his students, so he ended up writing it himself.

He has interacted constantly with geologists working in industry and for other state and federal agencies. Members of the public approach Ron with questions about land they own and potential resources. "He just is a wealth of knowledge about New Mexico and geology in general," says MARs Exploration and Energy petroleum geologist Mike Raines, "He's passionate about it [and] he's dedicated to it; I know he spends a lot of late hours. I've called him when I thought I'd be leaving a voice mail on his office phone and he was there. He answered the phone and he just [took] 30 to 40 minutes to talk to me about it."

Indeed, among his many awards, Ron received the Monroe G. Cheney Science Award from the Southwest Section of the American Association of Petroleum Geologists (AAPG) "for singular contributions and service toward the understanding of petroleum geology in the Southwest Region." "So that tells you about Ron, that he's regarded as being a major contributor to the petroleum geology of New Mexico and the surrounding area in particular... those aren't handed out willy-nilly," says Shelton. "You have to do something for them, and certainly he did more than his share."

Ron's service extends into the professional organization sphere. He served as editor for the online AAPG publication Search and Discovery for two and a half terms. Why a half term? Because he served two terms and then voluntarily stayed on for an extra year until a new editor could be appointed. "Ron did well beyond what he was expected to do and he actually kept working when he could have easily said, 'Look, this is in your ball court,'" says Shelton, "And [that's] typical of Ron from what I know if him. He goes the extra mile in whatever he does." And that really gets to the heart of Ron as a person. "My second favorite thing about Ron is how knowledgeable he is about New Mexico and how passionate he is about geology in general," says Raines, "My favorite thing is how he treats people."

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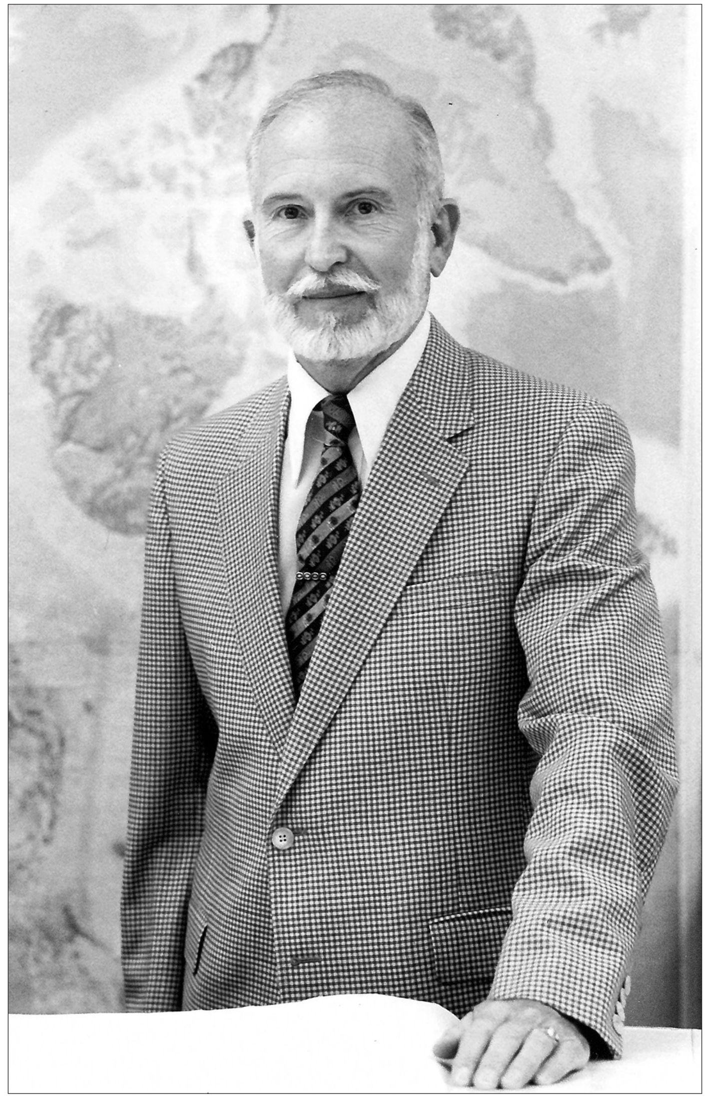
# In Memory of
# Lee A. Woodward

# 1931–2020

Lee Woodward, long a faculty member (1965–1997) and former chairman (1970–1976) of the Department of Earth and Planetary Sciences at the University of New Mexico (UNM), died on August 16, 2020, at the age of 89. His research contributed significantly to knowledge of New Mexico structural geology and tectonics, and the relationships of the structural history of an area to the occurrence of oil and gas and mineral resources. Lee spent much time studying geology in the field, and involved numerous graduate students in mapping 7.5-minute quadrangles, especially in the Nacimiento Mountains region. As an educator, he trained hundreds of undergraduate students in structural and field geology, as well as teaching introductory geology courses and advanced undergraduate and graduate courses. During his time as chairman the department's faculty expanded rapidly, attaining its highest number (14) to that point in its history, and he oversaw the strengthening of its undergraduate and graduate programs. Lee assumed leadership positions in several professional societies, and was active as an editor and contributor to New Mexico Geological Society field conferences and guidebooks. In addition to his work at UNM and in New Mexico, Lee also pursued research and published on aspects of the geology of his home state, Montana. These contributions are examined in more detail in the following paragraphs.

Lee Woodward was born on April 22, 1931, in Omaha, Nebraska, but his family moved to Montana in 1933, settling in Great Falls in 1935 and by 1940, in Missoula. From early in his life Lee traveled, was exposed to the natural world, and to a great variety of people. His father owned a construction firm, and took Lee along on many projects throughout Montana, often in small towns, during the depression years of the 1930s. Possibly a latent interest in geology was planted by periodic stays at a gold mine his father and others worked for a time. Later (1945), his family bought a ranch in the Bitterroot Valley south of Missoula, and Lee enjoyed fishing, hunting (sometimes for mountain lions), and backpacking through the Montana high country. During summers while in high school in the late 1940s he worked in construction for his father in several locations in Montana. While in college Lee spent the summers of 1950–1952 in Alaska, working on highway construction and as a longshoreman in the port of Valdez. These experiences likely were influential in shaping his personality, approach to life, expectations of others, and a very colorful vocabulary.

An indifferent student in high school, Lee enrolled in the University of Montana (Missoula) in 1950. There he married Katie, who would be his wife for the remainder of his life, nearly 68 years, and (less significantly) earned a Bachelor's degree in Business Administration in 1953. ROTC summer camp followed, and he was commissioned into the Army in October of that year. After four months of infantry and airborne training at Ft. Benning, Lee served most of his time in Germany, first as a platoon leader, and then company executive and intelligence officer.



Lee Woodward, 1990.

After returning to the U.S. and discharge from the army early in 1956, Lee again enrolled in the University of Montana, this time majoring in Geology, receiving his Bachelor's degree in 1958. He worked for the U.S. Bureau of Reclamation during the summer of 1958, on a project involving the geology of a potential dam site south of Glacier Park, and used this work as his Master's thesis, earning the Master's degree in 1959. Supported by a three-year NSF fellowship, he entered the Ph.D. program at the University of Washington, and wrote his dissertation on the structure and stratigraphy of the northern Egan Range in east-central Nevada, under Peter Misch. After receiving his doctorate in 1962, Lee worked briefly for Pan-American Petroleum Company in Montana and Wyoming, then taught at Olympic College in Bremerton, Washington from 1963 to 1965. In spring 1965 he interviewed for and was offered a faculty position at UNM.

Lee arrived at UNM in September 1965 with his wife and four children as a new assistant professor, and immediately began a heavy fall teaching load—structural geology, beginning field geology, and a geology-101 section. Knowing nothing of the local geology, he once remarked that in the field course "it was mainly a case of the blind leading the blind. I was however, enthusiastic and this helped to inspire the students." The roster of courses he taught expanded through the years, to also include advanced field geology, regional tectonics, mineral deposits, and subsurface geology. He immediately attracted graduate students, mentoring nine Master's students from 1967 to 1970. Throughout his career, Lee guided many graduate students, totaling 42 M.S. and five Ph.D. students. He coauthored papers and maps with some of them and many became lifelong friends.

In his first few years at UNM Lee quickly became knowledgeable about New Mexico geology and identified several areas of research interest. In addition to publishing Montana-based research, he initiated studies of spessartine dikes in the Sandia Mountains (Journal of Geology, 1970), and the tectonics of the Cordilleran foldbelt in southwestern New Mexico (with Lonnie Corbitt, his first doctoral student; AAPG Bulletin, 1973). However, his main focus of research in the 1970s became the geology of the Nacimiento Mountains. With a dozen Master's students Lee published geologic maps of 12 7.5-minute quadrangles, for the New Mexico Bureau of Mines & Mineral Resources (NMBMMR) geologic map series from 1972 to 1982, as well as major journal papers on the Nacimiento and Sierrita faults, a new Pennsylvanian formation, Triassic sandstone copper deposits, and the Morrison Formation of the area. This work was incorporated into Lee's monograph *Geology And Mineral Resources of the Sierra Nacimiento and Vicinity* (NMBMMR Memoir 42, 1987), one of the outstanding works on New Mexico geology of the last part of the 20th century.

During these early years at UNM, Lee also became heavily involved with the New Mexico Geological Society. He edited/coedited Guidebooks 21 (*Tyrone-Big Hatchet Mountains-Florida Mountains Region,* 1970), 25 (*Ghost Ranch,* 1974), and 30 (*Santa Fe Country,* 1979), as well as contributing numerous papers and road logs to these and other guidebooks through the years. With Stu Northrop, he also edited NMGS Special Publication 6 (*Tectonics and Mineral Resources of Southwestern North America*) in 1976, and was a contributor to the first edition of the *New Mexico Highway Geologic Map* (1984). For his contributions to NMGS he was awarded an honorary membership in 1989, and the 50th Guidebook (*Albuquerque Geology,* 1999) was dedicated to him.

Vin Kelley, chairman of the Geology Department since 1962, retired in spring 1970, and the department set about finding a new chairman. The process proved to be tortuous, involving a failed external search and initial selection of one of the current faculty, who proved quickly to be unsuitable. Finally, the Dean asked Lee to become acting chairman for the 1970–1971 academic year. He accepted, and then became the regular chairman from 1971 to 1976. His first year especially was difficult, as departmental programs were disorganized, its finances depleted, and no advice or assistance in understanding the many details of the position was offered by the previous chairman. Further, Lee was editing an NMGS guidebook, was president of the Albuquerque Geological Society, and establishing research programs, publishing, and mentoring nearly a dozen graduate students at this time. To say that this was an incredibly busy year for him would be an understatement.

Lee's time as chairman was extremely beneficial to the department. He led an effort to make the B.S. program more rigorous, and was instrumental in strengthening standards for admission into the Master's program, and in developing procedures for testing and evaluating the thesis research of Master's students, previously a process left principally to thesis advisors with varied results. He also enhanced the department's ties with industry, resulting in more job interviews and job offers for graduates and increased funding for graduate student research.

The six years Lee served as chairman had important consequences for the future of the department. When he became acting chairman, in fall 1970, the department consisted of 10 regular faculty. Lee hired nine new faculty members, some replacements for departing faculty but others in new positions, bringing the total to 14—the most in the department's history to that time—by the time his term as chairman ended. Further, four of the new faculty he hired (Brookins, Ewing, Wells, and Kues) eventually became chairmen of the department themselves. One, Steve Wells, is currently the president of the New Mexico Institute of Mining and Technology. Not all of the men he hired stayed long enough to contribute significantly to the department's growth, and to establish productive and sustained research careers in New Mexico and elsewhere, but most did, and that is an important part of Lee's legacy.

The end of his term as chairman released Lee from many time-consuming administrative duties, allowing more time for research and writing. His work in the Nacimientos continued, as well as studies of the structure, tectonics and Precambrian rocks in other parts of New Mexico and the greater Rocky Mountains region, and he published prolifically through the 1970s and 1980s. For NMGS guidebooks he and coauthors provided broad but detailed and very useful overviews of the structure/tectonics of various parts of the state (e.g., Four Corners region, 1973; central-northern New Mexico, 1974; Raton basin, 1976; San Juan basin, 1977;

Santa Fe area, 1979; Albuquerque area, 1982; northeastern New Mexico and adjacent states, 1987). In the context of early understanding of the new concept of plate tectonics, he collaborated with others to produce tectonic maps of the Rio Grande rift (for the Geological Society of America [GSA] Map and Chart series, 1975; NMGS, 1975; and NMBMMR Circular 163, 1978), as well as a guidebook for the Albuquerque basin part of the rift (NMBMMR Circular 153, 1976). Related journal articles included an early attempt to determine the rate of crustal extension across the Rio Grande rift (Geology, 1977), a comparison of the southwestern New Mexico overthrust belt with that of Utah and Wyoming (AAPG Bulletin, 1981), and a study of the age of the Abiquiu Formation, an early pre-rift sedimentary unit in central New Mexico (GSA Bulletin, 1981).

During this time Lee also worked with extractive industry companies as a consultant. These projects enhanced his interest in the structural/tectonic influences on mineral and oil and gas deposits, and resulted in numerous papers, typically with one or more coauthors, in the late 1970s to early 1990s. Many dealt with oil and gas prospects in New Mexico, including southwestern New Mexico (Oil and Gas Journal, 1980; Rocky Mountain Association of Geologists, 1984), the San Juan basin (AAPG Bulletin, 1979), the Raton basin (AAPG Bulletin, 1984), along the Nacimiento uplift (Rocky Mountain Association of Geologists, 1984), the Albuquerque basin (Oil and Gas Journal, 1985), and in central-western New Mexico (NMGS, 1986). Other papers incorporated studies of mineral deposits, such as gold mineralization in the Manzano Mountains (Mountain Geologist, 1978), Precambrian metallic mineralization in New Mexico (New Mexico Geology, 1981), mineralization associated with Tertiary intrusions along the Tijeras-Cañoncito fault (Geology, 1985), epithermal gold deposits remobilized from Precambrian strata during late Cenozoic continental rifting (Geology, 1990); a study of the tectonics, intrusive rocks and mineralization in the San Pedro–Ortiz porphyry belt east of Albuquerque (NMBMMR Bulletin, 1991), and studies of a copper-gold prospect in Lincoln County, gold mineralization in the Gallinas mining district, and a tectono-metallogenic map of mining districts in Lincoln County (all in the 1991 NMGS Guidebook).

Lee's research and publications concerning New Mexico geology lessened in the 1990s, as his focus shifted to Montana (see below). He continued to contribute overviews of structure, tectonics, and mineral resources to NMGS guidebooks and journals (e.g., on the geometry of the Nacimiento-to-Gallina fault system, 1992; the geology of the Santa Fe area, 1995; tectonics of the Four Corners region, 1997; tectonics and fracture reservoirs in the Cretaceous of the Raton basin, 1997; the Phanerozoic geologic evolution of the Albuquerque area, 1999; and Jurassic strata in east-central New Mexico, 2001). He collaborated on a tectonostratigraphic map of the Cordilleran orogenic belt in the Geological Society of America's Decade of North American Geology series (1993). And, he contributed to ongoing efforts to work out the movement of the Colorado Plateau during Laramide time, principally by examining stratigraphic constraints on right and oblique slip faulting on the east side of the plateau relative to its rotation, with papers in Geology (1994, 1997) and the GSA Bulletin (2001).

Lee Woodward retired from the regular faculty at UNM in December, 1997, and became a senior research professor. He was a familiar presence in the department until about 2008. His contributions to our understanding of New Mexico's geologic history were voluminous and significant, contained in more than 100 published papers and maps, and he will be remembered as one of the state's most productive and influential geoscientists of the later 20th and early 21st centuries. This would be a fine scholarly career for any research geologist. His accomplishments, however, do not end there.

Shortly before coming to New Mexico, Lee and Katie purchased a cabin in the Judith Mountains, northeast of Lewistown, in central Montana. They renovated and enlarged it, and returned to it nearly every summer for decades. It became Lee's base for continuing field work and research in Montana. His body of work in Montana is impressive— about 25 papers and maps, mostly published in journals and in various publications of the Montana Bureau of Mines and Geology (MBMG), as well as several books and book-length monographs. Most of these publications are studies of regional tectonics and the relationship of tectonics and structure to the formation of metallic resources. The following account is not exhaustive but is intended to indicate some of his most important and representative contributions that may not be known to his New Mexico colleagues.

An early, major paper on the tectonic framework of the disturbed belt of west-central Montana (AAPG Bulletin, 1981) was followed by a tectonic map of the fold and thrust belt in Montana (MBMG Geologic Map 30, 1982), and later by studies of Proterozoic faulting in central Montana (Mountain Geologist, 1995), and the tectonic evolution and geophysics of central Montana (Northwest Geology, 1997). Numerous studies involving silver and gold deposits are represented by papers on the tectonic origin of fractures for fissure vein emplacement in the Boulder batholith (Economic Geology, 1986), tectonic setting of gold and silver deposits in Proterozoic strata in west-central Montana (International Basement Tectonics Conference, 1992), structural control of lode gold deposits in the Tobacco Root Mountains (Economic Geology, 1993), metallic mineral deposits of the Judith Mountains in central Montana (MBMG Memoir 67, 1995), and a tectono-metallogenic map of the Dillon 1 x 2 minute quadrangle of Montana and Idaho (Tobacco Root Geological Society, 1990). Shortly after retiring Lee received the Distinguished Alumnus Award from the University of Montana, honoring his career contributions to geologic knowledge in both Montana and New Mexico.

After retirement, Lee turned to writing about the geology, history, and natural attractions of the central Montana country he liked so much. He produced four nontechnical books for general readers. The first, with former student Otto Schumacher, was entitled *Magnificent Journey: a Geologic River Trip with Lewis and Clark Through the Upper Missouri Breaks National Monument* (2004), which retraced the route of the Lewis and Clark expedition 200 years previously.

This was followed by *Field Guide to the Judith Mountains, Central Montana* (2009), with his daughter Ann, a guide to the geology, history, hiking, ghost towns, and natural history of the range in which he spent many of his summers. *Montana's Island Ranges* (2010) discussed the isolated mountain ranges that protrude through the surrounding prairie of central Montana. And lastly came *The Yogo Sapphire Mine, Montana* (2013), the geology and history of a world-class gem deposit in central Montana, published when he was 82 years old.

Lee was a man with a remarkable work ethic, a great sense of duty in fulfilling responsibilities he had undertaken, a straightforward, no-nonsense attitude, and strong convictions that included appropriate standards of behavior in people in general and in geology faculty in particular. His opinions were often expressed in unconventional, colorful language, no doubt acquired in his early years and in the military. All of his friends, students, and colleagues probably have their own favorite examples of Lee's distinctive ways of expressing himself. Mine occurred shortly after I arrived as a new faculty member in 1974. During an early faculty meeting, Lee was reporting some edict from the Dean that he disagreed with, and followed with the comment that the Dean "is so dumb that he does not have enough sense to pour warm piss out of his own boots." That was an eye-opener, but I soon learned that such language was a part of his unique persona, and more often than not reflected an accurate assessment of the subject in question. Lee did not suffer fools gladly, but was warm, generous, and supportive to those he found worthy.

One example of how Lee treated a young faculty member is contributed by Rod Ewing, who arrived at UNM at the same time as this writer. "As others do, I have many stories about Lee. For me the story that best captures his approach to life has to do with my teaching of mineralogy. As is true of many beginning faculty, my first mineralogy class was overly ambitious. Also, I had over a hundred students and no TA. The class did not go well. Finally, a delegation of students approached Lee with a long list of complaints. Lee called me into his office, and I sensed impending doom as he ran down the list of my shortcomings. When he came to the end of the list, he handed it to me and advised me to consider each complaint carefully, make adjustments as needed, and then get back to teaching the course. With a few profanities directed at some of the students who he judged to be lazy, he assured me that I had his full support, but he expected me to be successful and not to "f__ up". He could have crushed me at that vulnerable moment, but instead he left me in a good position to improve. I have always appreciated his very direct way of approaching any issue. Fortunately, as a veteran, I was not surprised by Lee's language—or the references to body parts and functions."

Lee expressed his own views on his career as a geology professor simply but eloquently: "As I look back on my career I feel extraordinarily fortunate to have had such good friends, including many of my former students. But perhaps most of all, I had an opportunity to do the kind of work that was both a vocation and an avocation—it was like being paid to have a hobby. Nearly all the research I undertook was a labor of love."

—Barry S. Kues, Emeritus Professor, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM