A comprehensive survey of faults, breccias, and fractures in and flanking the eastern Española Basin, Rio Grande rift, New Mexico

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ABSTRACT

A comprehensive survey of geologic structures formed in the Earth’s brittle regime in the eastern Española Basin and flank of the Rio Grande rift, New Mexico, reveals a complex and protracted record of multiple tectonic events. Data and analyses from this representative rift flank-basin pair include measurements from 53 individual fault zones and 22 other brittle structures, such as breccia zones, joints, and veins, investigated at a total of just over 100 sites. Structures were examined and compared in poorly lithified Tertiary sediments, as well as in Paleozoic sedimentary and Proterozoic crystalline rocks. Data and analyses include geologic maps; field observations and measurements; orientation, kinematic, and paleostress analyses; statistical examination of fault trace lengths derived from aeromagnetic data; mineralogy and chemistry of host and fault rocks; and investigation of fault versus bolide-impact hypotheses for the origin of enigmatic breccias found in the Proterozoic basement rocks. Fault kinematic and paleostress analyses suggest a record of transitional, and perhaps partitioned, strains from the Laramide orogeny through Rio Grande rifting. Normal faults within Tertiary basin-fill sediments are consistent with more typical WNW-ESE Rio Grande rift extension, perhaps decoupled from bedrock structures due to strength contrasts favoring the formation of new faults in the relatively weak sediments. Analyses of the fault-length data indicate power-law length distributions similar to those reported from many geologic settings globally. Mineralogy and chemistry in Proterozoic fault-related rocks reveal geochemical changes tied to hydrothermal alteration and nearly isochemical transformation of feldspars to clay minerals. In sediments, faulted minerals are characterized by mechanical entrainment with minor secondary chemical changes. Enigmatic breccias in rift-flanking Proterozoic rocks are autoclastic and isochemical with respect to their protoliths and exist near shatter cones believed to be related to a previously reported pre-Pennsylvanian impact event. A weak iridium anomaly is associated with the breccias as well as adjacent protoliths, thus an impact shock wave cannot be ruled out for their origin. Major fault zones along the eastern rift-flank mountain front are discontinuous and unlikely to impede regional groundwater flow into Española Basin aquifers. The breccia bodies are not large enough to constitute aquifers, and no fault- or breccia-related geochemical anomalies were identified as potential contamination sources for ground or surface waters. The results of this work provide a broad picture of structural diversity and tectonic evolution along the eastern flank of the central Rio Grande rift and the adjacent Española Basin representative of the rift as a whole and many rifts worldwide.

INTRODUCTION

The eastern Española rift basin and flank in northern New Mexico have recorded myriad geologic processes in the tectonic evolution of the Neogene Rio Grande rift (Fig. 1). As representative of the Rio Grande rift and many rifts worldwide, the Española rift flank-basin pair is one of several tectonically and topographically linked structural basin systems. The Española Basin represents only the latest of large geological features resulting from a series of major regional tectonic events that have affected northern New Mexico since Proterozoic time, all of which have left an imprint on the Precambrian basement rocks that compose the uplifted and exhumed rift flank (Fig. 2). Today, sediments within the basin shed from the rift flanks in the recent geologic past are important aquifers for the suburban and agricultural populations along the Rio Grande.

Faults, breccias, fractures, and other structures formed in the brittle regime of the Earth’s upper crust record past tectonic events in the Española Basin and adjacent rift flank. Moreover, rift-related brittle structures have influenced, and continue to influence, fluid flow—particularly the occurrence, recharge, storage, and flow of groundwater (Spiegel and Baldwin, 1963; Manning, 2009; Johnson et al., 2013). Rapid population growth and increasing demands on water resources have amplified the need for a better understanding of the geologic controls on groundwater. Thus, study of brittle structures in both geologic environments—the basin and the rift flank—provides a way to decipher tectonic history comprehensively, compare and contrast diverse structures, and examine their potential impacts on water resources.

This paper presents integrated data and analyses from fault zones and other brittle structures in the Española Basin region (Fig. 2). The results are interpreted to address several related topics: (1) the nature, diversity, and characteristics of brittle structures and how they might influence the occurrence of groundwater from rift flank to basin; (2) kinematic and stress history spanning the Laramide orogeny through rift formation; (3) investigation of fault trace lengths and the style of fault growth within the basin; (4) differences in
fault zone mineralogy and elemental geochemistry associated with different rock and sediment types; and (5) whether breccias commonly found in the rift flanks are fault related. The work in this paper complements and extends previous, similar work in the Española Basin and adjoining Santo Domingo and Albuquerque Basins (e.g., Heynekamp et al., 1999; Rawling and Goodwin, 2003; Minor and Hudson, 2006; Grauch and Hudson, 2007; Caine and Minor, 2009; Minor et al., 2013). The work is not intended to be an exhaustive treatment of any one type of data; rather the focus is on how different data types inform a holistic view of structural evolution in the brittle regime. The characteristics of individual fault zones, their growth, and their associations with ancient and present-day fluid flow in and along the flanks of a representative rift basin are emphasized.

A brief review of conceptual models for fault zone internal structure is provided because such models are used extensively in our detailed mapping and sampling, and for understanding the evolution of fault zones and the spatial continuity of their physical properties. The regional geology and previous work are briefly outlined to put the faults and other brittle structures studied into a broader context. A new geologic compilation map of part of the study area is presented along with new observations and data that characterize representative rift-related fault zones. Major elements of this broad fault characterization include host rock and fault rock lithologies, internal structures, lengths, widths, intensities, orientations, kinematics, mineralogy, and geochemistry in Proterozoic and Paleozoic rocks of the eastern Española rift flank as well as in poorly lithified, largely Neogene basin sediments. Fault zone characteristics in Proterozoic versus Paleozoic rocks are compared and contrasted with one another and with previous, similar work on fault zones in basin sediments. Kinematic models based on fault slip-surface data are used to explore the tectonic evolution of the rift flanks and associated basins.

A unique data set of geophysically expressed fault magnetic lineaments derived from high-resolution aeromagnetic data for the central Rio Grande rift (Grauch and Hudson, 2007) is used in this study as a proxy for fault trace lengths. Because many of the intrabasin faults are partially or completely concealed, this data set provides a more comprehensive view of their distributions, geometries, and lengths than can be gained from the limited surface exposures. The magnetic lineament data are used to document the distribution of fault lengths, intensities, and the style of fault growth within the Española Basin in comparison with surrounding rift basins and with fault trace length data from other tectonic settings globally.

Enigmatic but extensively distributed breccia bodies present in the Proterozoic rift flank basement are also characterized to evaluate their origin. These structures were included in this study because they are an integral part of the tectonic history of the rift and potentially influence fluid flow and water chemistry. Hypotheses regarding the origin of the enigmatic breccias are explored and include faulting, folding, magmatic processes, and possibly a bolide impact.

The data and analyses presented in this paper are organized by type and age, whereas the interpretations of the data and discussions are organized by topic. The paper can be read as a comprehensive, integrated document, or any of its parts can be read individually for those that may have specific interests.

## FAULT ZONE CHARACTERISTICS AND INTERNAL STRUCTURES

The internal structures, physical features, mineralogy, and elemental chemistry of fault zones that form in the brittle regime of the Earth’s upper crust are diverse. This paper considers fault zones that form in response to continental-scale contraction followed by extension during rifting. Brittle fault zones dominantly formed by fracturing of rock are commonly observed in the pre-rift sedimentary and crystalline rocks found along the flanks of the Rio Grande rift. However, a different mechanism of deformation, particulate flow that does not require brittle fracture, at least initially, is common in the poorly lithified, rift-fill sediments (Rawling and Goodwin, 2003; Minor and Hudson, 2006; Caine and Minor, 2009). Yet faults in both well-indurated rock and poorly consolidated sediments are characterized by common and distinctive structural components (Fig. 3). The components include a fault core where most of the strain is accommodated (Chester et al., 1993; Caine et al., 1996).
Figure 2. Generalized geology and geography of the eastern Española Basin and flanking regions of the Rio Grande rift showing geochemical sample and fault slip data collection locations. Modified from Grauch et al. (2009). Note inset area for more detailed geology of the eastern rift flank (see Fig. 4). MN—magnetic north.

EXPLANATION

Quaternary valley-fill alluvium and landslides
Pleistocene Bandelier Tuff, erupted from the Valles and Toledo calderas
Plio-Pleistocene Santa Fe Group (Ancha Formation, Tuerto Gravel, Puye Formation, and Sierra Ladrones Formation)
Plio-Pleistocene basalts and andesites of the Cerros del Rio volcanic field and Black Mesa
Oligocene-Miocene Santa Fe Group sediments (Tesuque and Chamita Formations)
Early Tertiary mafic volcanic rocks (Cieneguilla volcanic complex and undivided)
Late Eocene and Oligocene Espinaso Formation
Late Eocene and Oligocene intrusive rocks
Late Paleocene and Eocene clastic rocks of the Galisteo and Diamond Tail Formations
Mesozoic-Paleozoic clastic sedimentary rocks, undivided
Pennsylvanian sedimentary rocks of the Madera Group and Alamitos, La Pasada Formations, mostly limestones
Precambrian basement rocks, undivided
Major mapped fault or fault zone
Ball on down-thrown side; dashed where inferred; dotted where concealed
Major rivers and streams
Major roads
Geochemical sample and structural data collection sites (no inner black dot includes structure data only). Green, east-central Española (ECE) and blue, southeast Española (SEE) groups of Tertiary basin fill sediments; purple, includes Paleogene pre-rift moderately indurated sediments; red, Proterozoic or Paleozoic rocks.

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Strain localized in fault cores is manifested by brittle fracture and associated cataclastic grain size reduction due to frictional wear during shearing (e.g., Rutter et al., 1986) and/or by particulate flow where flow, rotation, and translation of grains are induced during shear lacking brittle fracture (Twiss and Moores, 1992; Evans and Chester, 1995; Rawling and Goodwin, 2003, 2006). Fault cores in rock and in sediment are discrete features that are commonly bounded by polished and striated slip surfaces in rock or sharp but grooved contacts in sediment. In both cases, these tabular elements provide information about fault synkinematic processes (Caine and Minor, 2009). In poorly lithified sediments, fault cores are commonly surrounded by a mixed zone (Heynekamp et al., 1999). Mixed zones are characterized by a range of chaotically arranged sediment to partially intact blocks of what were subhorizontally bedded sediments that have been physically entrained and rotated into parallelism with the fault core and translated from their original positions within the host sediments. Faults in rock commonly have a damage zone composed of small faults, veins, a variety of open fractures, and “drag” folds that surround the core (Fig. 3; Chester and Logan, 1986; Shipton and Cowie, 2001). Faults in sediment also show local damage beyond the mixed zone that is primarily marked by relatively sparse deformation bands and isolated slip surfaces, kinematically compatible with the fault zone (Heynekamp et al., 1999; Minor and Hudson, 2006).

The presence or absence, geometry, and types of structures, and the geochemical changes in fault-related rocks or sediments, such as due to cementation or hydrothermal alteration in any component, largely control the strength and permeability of fault zones. These properties may be different during deformation compared with times when the fault is not actively deforming. For example, fracturing localized in a clay-rich fault core due to high-strain-rate deformation during an earthquake can cause the fault to be a conduit for fluid flow (Evans and Chester, 1995), yet in the interim the low permeability of such clays can act as a barrier to flow across the fault (Fig. 3; Caine et al., 1996). If particulate flow is the dominant deformation mechanism within a clay-rich fault core, the fault may be a barrier whether it is deforming or not (Rawling et al., 2001; Caine and Minor, 2009). Clays can also mechanically weaken a fault, thus localizing deformation, whereas cementation can strengthen a fault causing distributed deformation and fault linking at segmented tip zones (Crider and Peacock, 2004). Taken together, each component plays a role in controlling strength and permeability. However, these zones of deformation can be quite heterogeneous, and it is possible to have multiple strands of cores, mixed and damage zones, splays, and relays that further complicate the internal structure of an individual fault zone (e.g., Caine and Forster, 1999; Wibberley and Shimamoto, 2003; Schöpfer et al., 2015).

### REGIONAL GEOLOGY AND PREVIOUS WORK

The 550-km-long Rio Grande rift is geologically expressed by several north-trending sedimentary basins (Fig. 1). From south to north, the Albuquerque, Santo Domingo, and Española Basins form the central part of the rift. These three basins are structurally linked, right-stepping, en echelon extensional basins filled with poorly lithified siliciclastic and volcaniclastic sediments (Fig. 2). The basin sediments also form the principal aquifers for domestic groundwater supply for cities such as Albuquerque and Santa Fe and surrounding areas. The onset of rifting marked by sedimentation and subsidence occurred in the early Oligocene with peak extension in the late Miocene and Pliocene (Kelley, 1979, 1982; Chapin and Cather, 1994; Hudson and Grauch, 2013; Koning et al., 2013). Estimates of extension in the Española Basin are from 10% to 17% (Woodward,

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Figure 3. Generic fault zone conceptual models depicting faults with fractures in rock, faults lacking fractures in poorly lithified sediments, and the geologic factors that may control fault zone permeability.
Recent studies suggest systematic changes in the regional stress field over time (e.g., Chapin and Cather, 1981; Gries, 1983; Erslev, 2001; Minor et al., 2013). Fault kinematic data from contractional structures in northern New Mexico and near the Española Basin show early Laramide east-west shortening followed by counterclockwise rotation of the shortening direction to a NE-SW orientation during the late Laramide and then a north-south orientation by mid-Tertiary time (Erslev, 2001). A subsequent change to ENE-WSW to east-west extension occurred during the Neogene development of the Rio Grande rift (Erslev, 2001). Progressive reactivation of Laramide contractional and strike-slip faults, as well as of deeper, crustal-scale Proterozoic structures, has also been thought to have played a role in accommodating tectonic stress during the evolution of the Rio Grande rift (Lewis and Baldridge, 1994; Karlstrom and Humphreys, 1998; Kellogg, 1998; Grauch et al., 2009; Minor et al., 2013).

Middle Proterozoic metasedimentary and metaigneous rocks form the crystalline basement of the Santa Fe Mountains on the east flank of the Española Basin (Fig. 2). In addition to many discrete fault zones, enigmatic breccias are present in these rocks at numerous localities throughout the Santa Fe mountains (Fig. 2; Kottowski, 1963; Bauer et al., 1997; Ilg et al., 1997; Read et al., 2004). In the Santa Fe Mountains, the origin of these breccias has been postulated to be related to faulting, magmatic processes, and possibly a bolide impact as there are also exposures of nearby shatter cones (Spiegel and Baldwin, 1963; Fankhauser and Erslev, 2004; McLelvain et al., 2006; Caine et al., 2007; Tegtmeyer et al., 2008; Fackelman et al., 2008; Wright et al., 2010). These breccias are similar to breccias associated with deformation along the Picuris-Pecos fault (Fig. 2), but the former do not include Paleozoic sedimentary clasts (cf. Wawrzyniec et al., 2007; Cather et al., 2008, 2011).

Proterozoic basement rocks are unconformably overlain by upper Paleozoic through Eocene sedimentary rocks that are mostly preserved beneath the rift basin sediments (Grauch et al., 2009). The Proterozoic and Paleozoic rocks have undergone variable degrees of Laramide contractional folding and faulting and variable erosion prior to rifting (Kelley, 1979; Lisben, 2013). Pre-rift, syn- and post-Laramide Eocene sedimentary (Galioteo Formation) and Eocene and Oligocene volcanic and volcaniclastic (Espinaso Formation) rocks unconformably overlie the Paleozoic and older rocks where they are locally preserved along the basin margins (Fig. 2).

The Española Basin is filled with a westward- to northward-thickening section of poorly lithified eolian, fluvial, and alluvial sediments of the Santa Fe Group (e.g., Connell et al., 1999; Koning et al., 2013). These sediments were deposited during the Miocene, Pliocene, and early Pleistocene when rift-related basin subsidence was at its peak (Smith et al., 2001; Dethier and Sawyer, 2006; Sawyer et al., 2006; Williams and Cole, 2007). Santa Fe Group sediments are largely siliciclastic sands and silts with varying amounts of conglomerate and gravel, but relatively few discrete beds of clay. There are lateral facies changes due to, among other factors, the effects of syndepositional growth faulting that accompanied rifting (e.g., May and Russell, 1994; Connell et al., 1999; Smith et al., 2001; Minor et al., 2006). Santa Fe Group deposits are 1.2 km thick in a borehole in the center of the Española Basin (Myer and Smith, 2006) and reach 3.1 km adjacent to the Pajarito fault (Fig. 2) as estimated from gravity data (Grauch et al., 2009).

Volcanism occurred episodically in and adjacent to the Española Basin during its development, beginning in the Miocene with silicic to intermediate eruptions in the Jemez volcanic field (Fig. 2; Smith et al., 1970; Goff and Gardner, 2004; WoldeGabriel et al., 2013). Lavas, pyroclastic deposits, and volcaniclastic sediments associated with this volcanism are interlayered with basin-fill sediments in the western Española Basin. Basaltic and andesitic lava flows from late Pliocene to early Pleistocene episodes of volcanism are present in the center of the Santo Domingo Basin, at the north end of the largely buried Cerrillos uplift separating the Santo Domingo and Española Basins, and in the northwestern Española Basin (Fig. 2; Thompson et al., 2006; Maldonado et al., 2013). During the latter part of the basaltic volcanism, voluminous silicic eruptions of the Bandelier Tuff occurred in the Jemez volcanic field at 1.6 and 1.2 Ma west of the Española Basin, resulting in formation of the Jemez caldera (Fig. 2; Smith and Bailey, 1968; Smith et al., 1970; Goff and Gardner, 2004).

Many basins in the Rio Grande rift are asymmetric half-grabens (Rosenthal, 1987). Normal faults in these grabens generally strike approximately north to NE, with steep, generally east and west dips perpendicular to the northerly trends of the rift basins (e.g., Chapin and Cather, 1994; Russell and Snelson, 1994; Grauch et al., 2009). Strata in the Española half-graben generally dip gently west, and major intrabasin faults dip generally east (Kelley, 1982; Chapin and Cather, 1994; Koning et al., 2013). Since about the end of the Miocene, the potentially seismic Pajarito fault has been the westernmost bounding fault of the Española Basin (Minor et al., 2006; Lewis et al., 2009; Fig. 2). It has accommodated 180 m to 1500 m of down-to-the-east displacement along a complex network of linked faults (Gardner and Goff, 1984; Lewis et al., 2009; Minor et al., 2013).

The east side of the Española Basin has no such major basin-bounding fault at the west-facing mountain front of the Santa Fe Mountains (Figs. 2 and 4; Read et al., 2004; Grauch et al., 2009). The “mountain front” and eastern basin margin are geomorphically complex, with stream-dissected, bench-like topography leading into the higher-relief core of the Santa Fe Mountains to the east. Most of the eastern basin margin is marked by a sedimentary contact between variably lithified Oligocene through Pleistocene sediments and crystalline Proterozoic basement (Fig. 2). Along a portion of this basin margin, the contact is underlain by Paleozoic carbonates deposited on Proterozoic basement (Fig. 4). The carbonate and basement rocks contain mountain front-parallel, open folds presumably formed during Laramide-age contraction. The mountain front area is locally cut by several discontinuous, short-trace-length, minor down-to-the-west, rift-related normal faults (cf. Read et al., 2004; Grauch et al., 2009; Koning et al., 2013).
Figure 4. (A) Geologic map of the western front of the Santa Fe Mountains compiled from new and existing 1:24,000-scale mapping by Kottlowski (1963), Kottlowski and Baldwin (1963), and Read et al. (2004). (B) Geologic structure map subset from A showing brittle faults, breccia bodies, folds, bedrock contact with basin-fill sediments, and sample and data collection sites. In both A and B, 30 m digital elevation model hillshade base map for topographic reference. MN—magnetic north.
Complex zones of structural accommodation mark the north and south boundaries of the Española Basin, with the Embudo fault system to the north and the Tijeras-Cañoncito fault system and broad Santo Domingo accommodation zone to the south and southwest, respectively (Fig. 2; Minor et al., 2006, 2013). These complex zones of deformation are composed of discrete and distributed zones of faults that have interacted with flanking and intra-basin north-south-striking faults. Many of these fault systems have complex components of extensional, oblique and strike-slip motion that separate the Española Basin from the San Luis and Santo Domingo Basins to the north and south, respectively, and that have also facilitated rift-flank surface uplift to the east and west (e.g., Smith et al., 2001; Koning et al., 2004; Minor et al., 2006, 2013).

Minor et al. (2013) presented hundreds of fault kinematic data collected within the Española Basin, Santo Domingo Basin and accommodation zone (SDBAZ), and northern Albuquerque Basin. Results of field observations and paleoassess analyses indicate that in the SDBAZ, normal-oblique faults are broadly distributed within two merging, NE-trending zones on its northwestern and southeastern sides. In contrast, faults in the Española and northern Albuquerque Basins are northerly striking normal to normal-oblique faults. Faults in the NE-trending zones have greater dispersion of rake values and strikes, greater dextral strike-slip components, and small to moderate clockwise apparent deflections of their tips. Field-based modeling results of relative ages among computed stress tensors suggest that far-field, approximately east-west–trending σ3 stress trajectories changed 45° to 90° clockwise into northwesterly to northerly trends within the SDBAZ. Fault-stratigraphic age relations constrain the stress changes to later stages of rifting, possibly as late as 2.7–1.1 Ma. Observations of faults and paleomagnetic evidence of post–2.7 Ma counterclockwise vertical-axis rotations are consistent with increased bulk sinistral-normal, oblique shear along the SDBAZ in Piocene and later time. Regional geologic evidence suggests that active rift faulting became increasingly confined to the Santo Domingo Basin and axial parts of the adjoining basins beginning in the late Miocene. It is inferred that the Santo Domingo clockwise stress changes developed coevally with the oblique rift segmentation mainly due to mechanical interactions of large faults propagating toward each other from the adjoining basins as the rift narrowed. Results also suggest that negligible bulk strike-slip displacement has been accommodated along the north-trending rift during much of its development.

### DATA AND METHODS

#### Data Acquisition, Observations, and Field-Based Characterization

Existing geologic, topographic, and aeromagnetic maps were inspected and local geologists were consulted to find outcrop exposures of faults. Once fault exposures were found, their traces were tracked in the field, on foot, to find the best localities for detailed study. Several new geologic maps were compiled from existing maps at scales ranging from 1:500,000 to 1:24,000 (New Mexico, New Mexico Bureau of Geology and Mineral Resources [2003]; Santa Fe, Kottlowski and Baldwin [1963] and Read et al. [2003a]; Seton Village, Kottlowski [1963] and Read et al. [2003b]; and the southern Española Basin, Read et al. [2004]). The arid environment and sparse soils of central New Mexico allow numerous outcrop and road-cut exposures of fault zones. If unnamed, faults were named for the locality where they were best exposed. Description of the structures, protolith and fault rock lithologies, and geometry of representative fault zones were completed. Geologic characterization of fault zones and other brittle structures provides geometric (e.g., location, length, width, and shape), rock-property (e.g., whether or not a fault zone might be a barrier, a conduit, or both with regard to groundwater flow), and geochemical attributes of brittle structures that can be used in future studies of water quantity and quality.

Detailed study of fault cores was completed by excavation and recording standard measurements along the cross-sectional exposures ranging from <1 m to >10 m in length. Measurements of down-dip variations in the width of each fault component were made. Estimates of fault displacement were made where possible based on observable piercing points or estimates of separation of stratigraphic units from existing map data, although very few such markers of offset were found or were previously mapped. Orientations of bedding, contacts, faults, fault-related slip surfaces and slip vectors, deformation bands, calcite veins, and fault-related fold hinges were measured where present. Representative samples of each fault zone component were collected and analyzed to determine: (1) microstructural and petrographic characteristics from thin section; (2) mineralogy; and (3) major, trace, and rare earth element concentrations.

#### Fault Zone Orientations, Slip Surfaces, and Modeling of Kinematics and Paleostresses

Fault slip surfaces were characterized as being principal or minor based on size and the architectural component in which they occur. Principal slip surfaces bound fault cores in faults that have traces generally more than several meters long in outcrop. Minor slip surfaces generally have trace lengths less than a few meters and include isolated single slip surfaces or networks of slip surfaces in fault damage zones. For each slip surface, the orientation of the plane and rake of silexines were recorded (Table S1). Shear sense was determined from interpretations of Riedel shears, fractures, and other fault surface decorations (e.g., Petit, 1987). Few measurable offsets were observed to help determine shear sense. The shear-sense determinations, which provide the directional component of the slip vector for each surface, were graded for quality using a scale of A = certain, B = likely, and C = uncertain. In some instances, fault slickensides directly cross-cut one another and were used to determine the relative timing of contractional, transform, and extensional deformation.
All fault slip data were compiled and plotted on equal area, lower hemisphere projections and grouped according to fault type, i.e., strike slip, reverse, and normal. Strain and paleostress analyses were completed for faults in the Paleozoic sedimentary and Proterozoic crystalline rocks flanking the Española rift basin. Minor et al. (2013) computed reduced paleostress tensors from fault slip data collected mostly within the Española rift basin sediments. Fault slip data presented here were used to: (1) estimate the orientations of principal strain and stress axes associated with the formation of fault sets; (2) assess the plausibility that particular fault sets were associated with known orogenic stages (e.g., Laramide versus Rio Grande rift) that contributed to the regional Cenozoic tectonic evolution; (3) compare with previous, similar analyses done by Minor et al. (2013) and from nearby localities; and (4) evaluate the role of preexisting structures in the tectonic evolution of the area.

Slip lineation plots of fault surfaces and striae were initially used to represent, determine, and organize fault sets as well as to determine the orientations of the infinitesimal principal shortening (P) and extension (T) axes using the computer program FaultKin (Marrett and Allmendinger, 1990; Allmendinger et al., 2012). For each fault plane and corresponding slip vector in the fault population, a “movement” plane was defined by a plane that contains the slip vector and the pole to the fault. If shear sense was determined from field criteria, the directions of P and T axes are found 45° from the pole to the fault plane within the “movement” plane and represent the principal axes of the incremental strain tensor for the fault or the “average” of all incremental strain tensors for a set of faults (Marrett and Allmendinger, 1990).

This approach can be used to evaluate whether fault sets are kinematically compatible with one another. Starting with groupings based on fault type (i.e., strike slip, normal, and reverse using FaultKin), an unweighted moment tensor summation was computed using Bingham statistics that link the P and T axes. For each fault type set, all individual P-T axes were plotted and superimposed on a fault plane solution that represents the average or best-fit conjugate fields for P and T based on the linked Bingham statistics for the set. Using FaultKin, individual faults whose P-T axes do not fall within the best-fit fields were iteratively removed until only the faults that fit within the average fields remained. The misfit data subsets were then further tested using the linked Bingham approach to evaluate their kinematic compatibility as distinct sets or in combination with other fault sets and further deconvolved if required. Misfit data that did not fit any of the deconvolutions and that did not make sense geologically were considered outliers.

The computed orientations of the P-T axes and P-T fields were then compared among the fault sets to determine if they are similar and how they compare with other estimates of the local and regional strain fields. Although more information can be obtained from the full displacement gradient tensor (Marrett and Allmendinger, 1990), the required fault displacement and surface area measurements were generally not obtainable in the Española Basin study area. Estimating these parameters using fault population statistics was also not deemed appropriate due to the high degree of uncertainty and variability of such fault properties in and flanking the Española Basin. Using the unweighted approach provides a uniform basis for comparison linked only to the geometry of the measured kinematic field data. Although the best-fit P-T solutions are not unique, they provide an initial approximation that also honors the geometry of the data.

A final step in the fault slip analysis was the comparison of results from the paleostress analyses of faults in the late Cenozoic Española Basin sediments from Minor et al. (2013) to the strain results presented in this paper from the rift-flanking Paleozoic and Proterozoic rocks. Such a comparison is used here to evaluate if the older rocks recorded similar deformation as that found in the younger sediments, elucidating the role of reactivation and/or decoupling of strain. In this study and in Minor et al. (2013), the direct inversion method of Angelier (1984) was used to estimate paleostress tensors from the fault slip data. The same input parameters are required for this approach as is used for the kinematic approach. The results were used to identify mechanically compatible, temporal groupings of data subsets and for comparison with the strain results. The Angelier (1984) method finds a least-squares minimization of the difference between the measured slip vectors and computed shear stress vectors within each fault plane. The Angelier method computes a best-fit reduced stress tensor consisting of the orientation of the principal stresses \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) where \( \sigma_1 > \sigma_2 > \sigma_3 \) (compressive stress positive) and the stress ratio \( f = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3) \). The value of \( f \) is indicative of the relative magnitudes of the three principal stresses. Further details regarding the paleostress analysis, including assumptions and limitations, are described in the appendix of Minor et al. (2013).

Aeromagnetic Data and Magnetic Fault Lineaments

High-resolution, reduced-to-pole aeromagnetic data provide a unique tool for mapping partially and wholly concealed faults in the central Rio Grande rift (Figs. 5 and 6; Grauch and Hudson, 2007). Subtle linear anomalies in these data are interpreted as the aeromagnetic expression of fault zones that offset Santa Fe Group sediments. The aeromagnetic anomalies arise from the tectonic juxtaposition of generally flat-lying sediments with differing magnetic properties (Hudson et al., 2008), and commonly require at least 30 m of vertical magnetic contrast (analogous to fault throw) to produce such anomalies common in the central Rio Grande rift (Grauch and Hudson, 2007). The linear aeromagnetic anomalies reflect the trace of magnetic contrasts caused by this stratigraphic juxtaposition somewhere along the fault, which, when projected to the Earth’s surface, may not correspond to mapped fault traces. However, at map scales more regional than 1:24,000, as is the case in our study, this discrepancy is negligible. Many of the linear anomalies also have distinct ends that are likely coincident with fault tips at any given erosion level, referred to here as effective fault trace length, and thus allow for the measurement of discrete and representative fault lengths as well as characteristic fault patterns throughout rift basins.
Even at regional scales, fault zones that are deeply eroded may have segmented linear aeromagnetic anomalies despite a continuous fault trace at the surface (Grauch et al., 2006). The discontinuities in aeromagnetic expression are caused by the uneven preservation of the stratigraphic juxtapositions with magnetic contrast. By inspection, only a small population of faults that have aeromagnetic expression are also deeply eroded. Therefore, this problem should be minimized when considering large populations of lineaments.

Computing the amplitude of the first derivative of the reduced-to-pole aeromagnetic data in map view (horizontal gradient magnitude, HGM) provides maps that enhance the locations of subtle, fault-related anomalies compared to other features of the aeromagnetic map (Figs. 6A and 6B). Magnetic fault lineaments are interpreted using linear ridges in the HGM map as a guide. Grauch and Hudson (2007) discussed in detail the process of, and additional considerations involved in, the interpretation of the magnetic fault lineaments for the central Rio Grande rift (Fig. 5). Some of the lineaments represent faults that juxtapose rock types other than Santa Fe Group, such as ones that are mapped within the Santa Fe Mountains where only Proterozoic rocks are present. Grauch et al. (2009) provided examples of types of faults that are expressed in the aeromagnetic data in the Española Basin, as well as faults in the northeastern part of the study area that do not produce anomalies at all.

Effective fault trace length data were extracted from the magnetic fault lineament maps (Tables 1 and S2 [see footnote 1]; Fig. 5A) and evaluated for systematic distribution in the Española Basin and adjacent Santo Domingo and Albuquerque Basins to provide regional context and to fully utilize the unique data available. The quality of functions used to model the distribution of fault trace length data was evaluated primarily following the statistical methods of Clauset et al. (2009).

**Mineralogy and Elemental Chemistry**

Samples were collected to compare the mineralogy and chemistry of fault-related rocks and sediments with their respective protoliths to evaluate potential changes due to brittle deformation and associated fluid flow (Tables S3 and S4 [see footnote 1]). Representative samples were excavated from at least several centimeters below outcrop faces to avoid the most weathered material. For each exposure, at least one sample was collected from adjacent protolith(s), fault core(s), and/or breccia(s). Whole rock and sediment samples were analyzed for mineralogy by powder X-ray diffraction (XRD) and for chemistry of major, trace, and rare earth elements using inductively coupled plasma–mass spectrometry (ICP-MS).

Powder XRD analyses were completed at the U.S. Geological Survey (USGS) laboratory in Boulder, Colorado. The raw X-ray spectra were analyzed using RockJock software (Eberl, 2003) briefly described below. All samples were crushed to a 150 μm powder, micronized in a mill to an average grain size of ~5 μm, and then side loaded into holders to insure random mineral orientation.
Figure 6. (A) Example of horizontal-gradient magnitude of reduced-to-pole aeromagnetic data used to infer the magnetic fault lineaments for parts of the Barrancos and Agua Fria fault systems in the Española Basin; modified from Grauch and Hudson, 2007. (B) Detailed example of faults interpreted from aeromagnetic data (white) and mapped faults (pink) overlaid on raw data from A (modified from Grauch et al., 2009). (C) Española Basin fault map showing the lengths, geometries, and intensity of basin-scale faulting from aeromagnetic lineaments (pink) and mapped faults (black). See Fig. 5 for map locations.
The samples were X-rayed with Cu-K alpha radiation from 5° to 65° two theta. Using the RockJock computer program, mineral phases were identified and then a standardless analysis (i.e., no added internal standard) was used to convert the XRD intensity data into mineral weight percent (Eberl, 2003). Integrated XRD intensities were determined by whole pattern fitting (Smith et al., 1987) using a database of XRD patterns of pure minerals. Several patterns of individual minerals from the database were scaled simultaneously and summed together to create a calculated pattern that was compared to the measured sample pattern. The scaling factors were adjusted automatically until the degree of fit between the measured and calculated patterns was minimized. The error in the analyses is approximately ±3 wt% (one standard deviation) at 50 wt% of a mineral (Eberl, 2003). Each sample underwent at least two RockJock analyses.

Major and trace element chemistry was determined using four-acid digestion (±10% analytical error; see Briggs and Meier, 2002) and rare earth elements using a sodium peroxide sinter (±5% analytical error; Meier and Slowik, 2002) analyzed by ICP-MS. Elements such as Na, S, As, and Cd were desirable to include in the data sets, however Na is not a part of the ICP analysis suite and S, As, and Cd were at or below detection limits.

The abundances of elements associated with impactites, including Ir, Cr, and Ni, were determined from breccia, fault, and protolith samples by instrumental neutron activation analysis (INAA; Table S5 [see footnote 1]).

### TABLE 1. SUMMARY AND ANALYTICAL STATISTICS FOR MAGNETIC FAULT LINEAMENT LENGTH DISTRIBUTIONS IN BASINS OF THE CENTRAL RIO GRANDE RIFT

<table>
<thead>
<tr>
<th>Basin</th>
<th>Survey area (km²)</th>
<th>Number of faults</th>
<th>Number of faults per unit area (faults/km²)</th>
<th>Mean length (km)</th>
<th>Median length (km)</th>
<th>Maximum length (km)</th>
<th>Minimum length (km)</th>
<th>Percent data with power-law fit</th>
<th>Regression coefficient (R²)</th>
<th>Power-law exponent (C)</th>
<th>Comment</th>
<th>KS Test p-value</th>
<th>Likelihood ratio (R²) (Plaw vs. Exp)</th>
<th>Likelihood ratio (R²) (Plaw vs. Lnorm)</th>
<th>Favorable distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>All basins combined (censored*)</td>
<td>6964</td>
<td>575</td>
<td>0.082</td>
<td>4.3</td>
<td>3.3</td>
<td>35.4</td>
<td>0.54</td>
<td>100.0</td>
<td>0.88</td>
<td>1.33</td>
<td>All data</td>
<td>0.811</td>
<td>1.85</td>
<td>0.783</td>
<td>Plaw</td>
</tr>
<tr>
<td>Albuquerque</td>
<td>4603</td>
<td>328</td>
<td>0.071</td>
<td>4.6</td>
<td>3.3</td>
<td>35.4</td>
<td>0.54</td>
<td>100.0</td>
<td>0.90</td>
<td>1.29</td>
<td>All data</td>
<td>0.540</td>
<td>1.34</td>
<td>1.05</td>
<td>Plaw</td>
</tr>
<tr>
<td>Santo Domingo</td>
<td>1279</td>
<td>96</td>
<td>0.075</td>
<td>4.4</td>
<td>3.6</td>
<td>16.8</td>
<td>0.57</td>
<td>100.0</td>
<td>0.84</td>
<td>1.17</td>
<td>All data</td>
<td>0.042</td>
<td>−1.02</td>
<td>−1.87</td>
<td>Lnorm</td>
</tr>
<tr>
<td>Espanola</td>
<td>1102</td>
<td>117</td>
<td>0.106</td>
<td>3.4</td>
<td>2.7</td>
<td>12.5</td>
<td>0.82</td>
<td>100.0</td>
<td>0.88</td>
<td>1.46</td>
<td>All data</td>
<td>0.774</td>
<td>2.33</td>
<td>−0.204</td>
<td>Plaw or Lnorm</td>
</tr>
</tbody>
</table>

Summary statistics for power-law exponents (C)†

| All C, maximum | 2.60 |
| All C, minimum | 0.88 |
| 100% of data, C maximum | 1.46 |
| 100% of data, C minimum | 1.17 |
| 100% of data, C median | 1.29 |
| R² = 0.95, C maximum | 1.65 |
| R² = 0.95, C minimum | 1.14 |
| R² = 0.95, C three-basin median | 1.16 |
| Percent fit at R² = 0.95, maximum | 88.0 |
| Percent fit at R² = 0.95, minimum | 71.9 |

Abbreviations: KS—Kolmogorov-Smirnov statistic; vs.—versus, Plaw—power-law distribution, Exp—exponential distribution; Lnorm—lognormal distribution.

*See text (Challenges of Interpreting Fault Length Data and Derived Power-Law Exponents section) for explanation of “censored”.

†All C refers to values of C from All basins combined and Albuquerque, Santo Domingo, and Espanola basins. 100% of data refers to C values for all basins combined and the individual basins with a fit using 100% of the data for each. The three-basin median only includes Albuquerque, Santo Domingo, and Espanola basins. The combined basin median includes All basins combined and Albuquerque, Santo Domingo, and Espanola basins.
samples were irradiated in the USGS TRIGA reactor at a flux of $2.5 \times 10^{12}$ for 8 hr. Three sequential counts around 7 d, 14 d, and 65 d after the irradiation were made on both coaxial and planar germanium detectors. A summary of the INAA procedure used at the USGS is given in Budahn and Wandless (2002). Precision and accuracy for Cr and Ni each range from 1% to 5%, with a precision error of >10% for Ir based on counting statistic errors. Accuracy is based on replicate analysis of USGS standard reference materials, including BHVO-1.

### Statistical Analyses of Fault Zone Mineralogy and Geochemistry

The mineralogical and elemental data were evaluated for statistically significant differences between protoliths and fault rocks or breccias using non-parametric statistics (e.g., Wilcoxon, 1945). Due to the small sample sizes associated with each fault zone component, a statistical distribution was not assumed. Although the sample sizes are small, being from $n = 3$ to $n = 16$, with a mean of 7 samples, the Mann-Whitney rank sum is a robust measure of median differences for representative data pairs (Helsel and Hirsch, 2002). Groupings of the data were based on the age of the rocks or sediments and whether they came from the basin flanks or from within the basin. Each fault zone component from faults of all ages and locations was evaluated using a hypothesis test implemented through the Mann-Whitney rank sum. The hypothesis tested in each case was whether the component (e.g., protolith versus fault rock) medians for each mineral or element analyzed were different. Box plots provide a way to visually inspect the full range of mineralogical and chemical compositions of fault components or breccias compared with adjacent protolith samples. For each mineral or element pair where there was a statistically significant difference based on the hypothesis test, U statistics (nonparametric test of the null hypothesis, e.g., Mann and Whitney, 1947), and $p$ values (probability that the null hypothesis is true, e.g., Helsel and Hirsch, 2002) the factor of exceedance was also computed and plotted directly on the box plots.

### FIELD-BASED OBSERVATIONS

#### Faults Primarily in Proterozoic Rocks

The Santa Fe fault (also called the Santa Fe River fault in Grauch et al. [2009]) is a NE-striking fault with several adjacent faults exposed nearby (e.g., Santa Fe West fault and the Small fault; cf. Figs. 4, 7, and 8). The Santa Fe fault was mapped by Read et al. (2003a) and recognized in geophysical data by Grauch et al. (2009). Although one of the longer faults in the eastern rift flank, the map pattern shows little separation of the units it transects suggesting little displacement, consistent with geophysical data (cf. Grauch et al., 2009). At a western locality near the mapped trace of the Santa Fe fault, a NNE-striking, steeply ESE-dipping, WNW-directed reverse fault is exposed (Fig. 7, location E). It is fully within unaltered Proterozoic granite and shows a well-developed, single fault core bounded on the hanging-wall side by a discrete polished and striated principal slip surface and on the footwall side by a more disrupted but discrete contact. The core is up to a meter thick, with distinctive breccia composed of subrounded, probably locally derived clasts of granite in a highly indurated matrix composed of silica and fine-grained sericite (white mica) consistent with hydrothermal alteration (Fig. 9B; e.g., Hemley and Jones, 1964; Parry et al., 2002). A damage zone surrounds the core and is composed of minor hematite-coated slip surfaces, hematite veins, and open, iron hydroxide-coated fractures that are reduced in number away from the core.

The likely Santa Fe fault proper is well exposed at the easternmost locality along its mapped trace (Fig. 7). Within the 8-cm-thick, isoclinally folded, clay-rich fault core, slickenlines and shear sense provide evidence for early sinistral strike slip and reverse slip as well as stratigraphic separation evidence for later normal dip-slip reactivation. Its poorly developed damage zone is primarily characterized by higher joint density than in the protolith. The compositional layering in the Proterozoic hanging-wall metasedimentary protoliths is nearly at right angles to the fault surface. Similar to the reverse fault exposed in the western locality, there is field evidence for argillic hydrothermal alteration in the footwall granite, but it appears restricted to the damage zone and is not apparent in the clay-rich core.

Numerous, small-displacement minor faults were observed in the Proterozoic basement rocks. These are single, commonly isolated polished and striated slip surfaces that show <10 cm of offset and short trace lengths on the order of several meters. The polish is commonly composed primarily of quartz, but some surfaces are coated with hematite. Many of the single slip surfaces are open features with no internal mineralization, resulting in visible apertures ranging from microns to several millimeters wide.

At the 1:24,000 to regional scales, aeromagnetic data reveal a north-trending magnetic fabric in Proterozoic basement rocks along the mountain front on the east side of the Española Basin (Grauch et al., 2009). Although the fabric results from a geophysical signal, it indirectly correlates with a number of geologic structures at the surface including Proterozoic lithologic contacts, major fold axes in the overlying Paleozoic sedimentary rocks, and several relatively short-trace-length brittle fault zones (Figs. 4, 5, and 6; cf. Read et al., 2004; Grauch et al., 2009).

#### Breccias in Proterozoic Rocks Not Related to Fault Cores

Although breccias are globally common rock types, their origins are commonly challenging to determine (e.g., Jébrak, 1997; Woodcock et al., 2006). Using a holistic approach with map data, outcrop characteristics, structural data, and geochemistry (including discriminant analyses of Ir, Cr, and Ni concentrations as characteristic indicators of meteoritic origin) relative to other brittle fault and structural feature data, the viability of the different hypotheses is more effectively evaluated. The enigmatic breccias found in the Proterozoic rocks of the Santa Fe Mountains are characterized by autoclastic textures in which the clasts are derived from the parent rock and do not appear to have been transported large distances (Figs. 4 and 10).
Figure 7. Geologic map detail from the northern portion of Figure 4 (modified from Kottlowski, 1963, Kottlowski and Baldwin [1963], and Read et al. [2004]) and structural data. Fault characterization, structural data, and sample collection sites are shown in the map with capital letters (no orientation data was collected at sites without letters). Map symbology, unit colors, and names are the same as in Figure 4. MN—magnetic north. Lower hemisphere, equal area projections show fault slip data for major faults (solid lines) and minor slip surfaces (dashed lines). North is at the top of each plot. Great circles represent measured slip planes: blue = reverse and thrust faults; green = strike-slip faults; red = normal faults. Slip arrows on great circles show direction of hanging-wall motion.
Figure 8. Geologic map detail from the southern portion of Figure 4 (modified from Kottlowski [1963], Kottlowski and Baldwin [1963], and Read et al. [2004]) and structural data. Fault characterization, structural data, and sample collection sites are shown in the map with capital letters (no orientation data was collected at sites without letters). Map symbology, unit colors, and names are the same as in Figure 4. MN—magnetic north. Lower hemisphere, equal area projections show fault slip data for minor slip surfaces (dashed lines) on the lower left for two localities shown on the map. North is at the top of each plot. Great circles represent measured slip planes: blue = reverse and thrust faults; green = strike-slip faults; red = normal faults. Slip arrows show direction of hanging-wall motion. Joint data in rectangular box on the right side are shown in Kamb contoured, lower hemisphere, equal area projections for localities shown on map and in Figure 7. Contours in shades of green (protoliths, PL) and brown (damage zone, DZ) represent joints in Proterozoic rocks (footwall, FW; hanging wall, HW); contours in shades of darker blue (PL) and lighter blue (DZ) represent joints in Paleozoic rocks. N—number of data; C.I.—contour interval.
Figure 9. Outcrop photographs of fault zones and breccias in the Española rift flank and basin (see Fig. 7 and Table S1 [see footnote 1 for localities]). (A) Santa Fe fault west showing damage zone and fault core, looking northeast (tan eroded region in the center of the photo). Tree at left is about 4 m tall. (B) Detail of the hydrothermally altered and brecciated fault core shown in A. Note the rounded clasts of orthoclase granite within the core. (C) Fault core clay-rich gouge from the Santa Fe fault east. Note the sinistral (based on Riedel shears) strike-slip slickenlines overprinted by reverse dip-slip slickenlines (yellow lines). Pencil for scale. (D) Autoelastic breccia in orthoclase-rich Proterozoic granite in the northern part of the Española rift flank showing angular clasts and a lack of hydrothermal alteration. (E) Autoelastic breccia in chloritized Proterozoic amphibolite gneiss in the vicinity of the shatter cone locality and Nuns curve. (F–H) Hyde Park Road fault and the Proterozoic-Paleozoic unconformity at Nuns curve on New Mexico Highway 475. (F) View looking northeast where Paleozoic limestones are deposited on the chalky-white hydrothermally altered Proterozoic granites. The Hyde Park Road normal fault and its clay-rich fault core can be seen in the center, lower portion of the photo. (G) View looking southeast where the brown, steeply SE-dipping clay-rich principal slip surface (red line) of the main normal fault can be seen in the middle of the photo in rocks below the unconformity. A minor reverse-slip fault surface can be seen just below and to the right of the extensional principal slip surface (PSS). Minor extensional slip surfaces can also be seen in the Paleozoic limestone hanging wall above the unconformity. (H) Piece of clay-rich fault gouge from the fault core held in the same orientation as in outcrop. Note the white clasts of hydrothermally altered wall rock entrained in the gouge. (I) Complex, 8-m-wide fault core of the Florencio normal fault. The view is looking southeast. pG indicates Proterozoic and pP indicates Paleozoic rocks, respectively. (J) Photo looking northwest at the Proterozoic-Paleozoic unconformity. The reddish-gray Proterozoic rocks below the unconformity are brecciated, and isolated subrounded boulders of this material can be seen in the tan Paleozoic limestone above the unconformity. (K–M) Examples of intrabasin faults (faults in sediment, FIS). (K) San Isidro Crossing fault, looking north, showing two clay-rich fault cores in sharp contact with the siliciclastic protolith. Backpack in lower right is about 50 cm high. (L) Road fault, looking north, with an entrained bed of calcite-cemented quartz-rich sand on its downthrown side. (M) Sand-rich and highly mixed core of the Church fault showing white, botryoidal silica cement. (N) Closeup of a large, noncylindrical internal ridge and furrow slip surface in the clay-rich fault core of the Santa Clara fault; such fault core textures were interpreted by Caine and Minor (2009) as evidence for ductile slip in initially unconsolidated materials below the paleo-water table.
Figure 10. Crossed-polarized light (unless noted otherwise) photomicrographs of enigmatic and fault-related breccias in Proterozoic rocks of the east flank of the Española Basin. (A) Rounded to subrounded clasts of the west Santa Fe fault breccias. (B) Clay-rich fault gouge of the Hyde Park Road normal fault also shown in Figure 9H. Note the subrounded clasts of multiply deformed granitic material and attached matrix. (C) Angular clasts of granitic materials a few hundred meters west of the mapped trace of the Picuris-Pecos fault in Deer Creek. Note the systematically oriented and strained calcite veins (sc) and preferential sericitic alteration (sa) of plagioclase grains. (D) Angular and sericitized grains of the Hyde Park Road breccias. Minor unstrained calcite is also present in the pore spaces. (E) Grain-size sorting at one margin of a cataclastic breccia vein from the Bishops Peak breccia. The opposite side of the vein shows the same texture. Plagioclase grains lack evidence for hydrothermal alteration in this most-distal breccia with respect to the location of the shatter cones farther north. (F) Interstitial and unstrained secondary calcite in the Gabaldon breccia. (G) Argillically altered matrix and plagioclase clasts of the footwall breccias from the Hyde Park Road fault. (H) Plane light view of the argillically altered angular clasts and matrix of the Polai breccia. (I) Plane light view of iron hydroxides in interstitial matrix pore spaces of enigmatic breccias from Upper Canyon Road east of Santa Fe. Note the felted brown sericite (sa) in angular plagioclase clasts and matrix.
The Proterozoic, generally granitic clasts in the enigmatic breccias are indicative of a single brecciation event, as none show evidence for internal brecciation from an earlier event. Some exposures show megabreccia with near-matrix-supported, decimeter-sized clasts, whereas others show incipient breccias primarily composed of highly fractured rock with only minor development of matrix material. The matrix of the breccias is most commonly composed of finer-grained parent material with variable amounts of quartz, feldspars, and in some cases secondary nearly opaque iron hydroxides (Fig. 10; cf. Wright et al., 2010). At one of the most distal breccia localities, near Seton Village, there are microbreccia veins composed of highly angular autclastic fragments that show clear evidence of flow by grain-size sorting along their margins (Fig. 10E). Near faults, calcite in the breccias forms systematically oriented microveins that cut the clasts and matrix and contain numerous twins indicative of strain. Other calcite occupies pore spaces, in some cases forming after iron hydroxides within the matrix, and this calcite shows little evidence of twinning (Fig. 10F). No evidence for melting was found in the breccias in the form of amorphous materials, pseudotachylites or other shock-related features such as planar deformation features as was hypothesized or found by previous workers in association with shatter cones in the area (Fackelman et al., 2008).

Unlike the fault breccias, there is little macroscopic field evidence for significant hydrothermal alteration of the enigmatic breccias, as the feldspar and biotite grains in them are generally fresh and vitreous (Fig. 9B compared with Fig. 9D). The exception is where breccias are near map-scale faults or where breccia bodies have been cut by faults. As well, the clasts are angular compared with the subrounded clasts found in breccias associated with fault cores. In thin sections from breccias near mapped faults, argillic hydrothermal alteration is evident from the preferential development of clay and sericite in plagioclase in the breccia clasts and in the matrix. In some areas, the fine clays in plagioclase have similar optical extinction between the clasts and matrix and biotite appears only somewhat altered.

The breccias occur as a wide variety of bodies including small (length of a few meters) and large irregular bodies (hundreds of meters), and tabular to tortuous dikes (Figs. 4, 7, and 8). The map patterns and outcrop observations of the breccias show a variety of intrusive contacts with their host country rocks and thus do not support the idea that the breccias were part of an ejecta blanket (cf. Newsom et al., 2007; Fackelman et al., 2008) or large-scale layering as are found at other impact sites such as the Sudbury impact structure in Ontario, Canada (Cannon et al., 2010). Importantly, at the map scale, breccias exist at or below the structural elevation of the shatter cones described by Fackelman et al. (2008) and no major faults separate these features. The map pattern of the breccia bodies shown in Figure 4 indicates that all major Proterozoic lithologies (granite, paragneiss, and amphibolite) are brecciated, but no Paleozoic or younger rocks are brecciated, at least not in a similar manner (cf. Wright et al., 2010). The map pattern also shows that the breccias form an arcuate pattern, particularly in the granites of the southwestern part of the map area, with apparent oblong radial symmetry about the location of the shatter cones (Fig. 4). The map pattern and outcrop observations show that most of the breccia bodies are not spatially associated with major faults and that the bodies are much more extensive than the fault traces. Where faults are co-located with breccias, the faults cut and deform the breccias. Figure 9J shows subrounded cobbles and boulders of brecciated Proterozoic granite completely embedded in Madera Group limestones at the Paleozoic-Proterozoic unconformity. This contact shows none of the typical features of a fault zone such as slip surfaces, gouge, kinematic veins, or internal brecciation.

**Faults in Both Paleozoic and Proterozoic Rocks**

Faults that involve Paleozoic rocks share many characteristics with those in the Proterozoic rocks. Based on mapped stratigraphic separation and kinematic field measurements, the Florencio fault shows ~200 m of down-to-the-SE net displacement distributed across a complex fault core up to 8.4 m wide (Fig. 7, locality D; Fig 9I; Table S1 [see footnote 1]). It juxtaposes Pennsylvanian, undifferentiated Madera Group calcite-cemented, fossiliferous quartz sandstone against Proterozoic foliated granitic gneiss. The fault core is texturally and compositionally heterogeneous. On the footwall side, the core shows a 2.4-m-wide breccia composed primarily of chloritically altered Proterozoic host rock. A 6-m-wide zone of clay-rich gouge with poorly developed phacoidal cleavage sits in sharp contact with the footwall breccia along a weakly striated slip surface. The gouge is internally complex with numerous synthetic stringers of foliated and variegated gouge, small chaotic folds, and entrained blocks of sandstone, some with dismembered but well-developed slip surfaces. The hanging-wall damage zone is also in sharp contact with the clay-rich core and contains numerous small-displacement normal faults that are synthetic and antithetic with respect to the footwall slip surface (Fig. 9I).

Another example of a fault involving Proterozoic and Paleozoic rocks is the Hyde Park Road fault that is well exposed in a road cut along New Mexico Highway 475 at Nuns curve (Figs. 7, locality K; Figs. 9F–9H). The fault cuts a complex assemblage of Proterozoic amphibolite and orthogneiss with evidence of hydrothermal alteration as well as the overlying unconformity with Madera Group limestone. The rocks are characterized in the field by chalky white plagioclase that has been largely transformed to sericite and clay. However, biotite grains in the altered Proterozoic rocks are relatively fresh. Alteration likely occurred in the limestone in the hanging wall of the fault as well, but it is not obvious in outcrop. The alteration forms an envelope spatially associated with the fault that extends several to a few tens of meters away from it. Numerous calcite veins and small “fibrous” calcite slip surfaces were observed in the limestone, many with strike-slip and dip-slip kinematic indicators. A damage zone surrounding the fault core is marked by numerous small normal and oblique-normal, synthetic and antithetic slip surfaces that cut both the limestone and crystalline rocks. This network of subsidiary faults appears to be concentrated in the hanging wall and is up to a few meters in width. The trace length of the fault is at least 300 m based on its mapped extent (Fig. 7). A well-exposed, discrete fault core exists and continuously cuts its protolith the full length of the exposure. The core is composed of brown clay-
rich gouge with moderately well-developed phacoidal cleavage. The gouge also has numerous rounded to subrounded clasts of the altered Proterozoic rock embedded within it (Figs. 9H and 10B). The core is highly discrete, 3–5 cm wide, and bounded by well-developed principal slip surfaces with normal dip-slip striae. Total displacement is difficult to gauge at the exposure because piercing points are not present locally, but is likely to be on the order of tens of meters based on the lack of stratigraphic separation at map scale and the amounts of offsets observable in road cuts. Although fault cores in Proterozoic and Paleozoic rocks were less commonly observed compared with those in basin sediments, measured fault cores have a median width of 65 mm (mean = 1.7 m, n = 8) (Fig. 11).

**Joints in Proterozoic and Paleozoic Rocks**

The bedrock of the eastern Española rift flank is pervasively jointed (Fig. 8). Joints form networks of subvertical planar to curviplanar discontinuities that fall into a few diffuse sets striking NE, ENE, NW, and WNW. There also is a set of subhorizontal joints found throughout the study area. The joints are open fractures, some with iron-oxide staining, but no other evidence of alteration or mineralization is present. Observed trace lengths range from a few meters to tens of meters transecting entire outcrops. Joint spacing is generally large, ranging from one to a few joints per meter to as much as several joints per decimeter, particularly where the joints are near faults. Fault damage zones contain joint sets not found in adjacent protoliths, yet their orientations are similar to the regional orientations (Fig. 8).

**Proterozoic-Paleozoic Unconformity**

The unconformity between Proterozoic crystalline and Paleozoic sedimentary rocks is an important lithological and structural discontinuity that could impact water resources. The unconformity is well exposed in a number of places along the eastern rift flank of the Española Basin (Figs. 7, 8, 9F–9H, and 9J). The localities observed all show limestone or marly limestone deposited on locally regolithic gneisses or brecciated equivalents. The unconformity is generally angular where there is compositional layering in the gneisses and a nonconformity where metaigneous rocks are present in the basement. Although no evidence was found to support the contact being a fault itself, numerous small-displacement extensional faults and their damage zone fractures cut the unconformity and the sedimentary and basement units. Many open joints also cut the unconformity and are deflected in dip angle as they pass from the limestone into the gneiss and die out rapidly. Calcite veins are more common in the carbonates, and they generally do not transect the unconformity contact.

**Faults in Tertiary Basin-Fill Sediments**

As discussed in Rawling et al. (2001), Rawling and Goodwin (2003), Minor and Hudson (2006), and Caine and Minor (2009), faults in poorly lithified, siliciclastic basin-fill sediments are different than faults in well-indurated rocks, with the dominant architectural element being a clay-rich fault core. This also is true for such faults in the Española Basin and will only be briefly discussed here. Most of the faults exposed in the basin sediments show well-developed and discrete, single clay-rich fault cores or discrete single slip surfaces with poorly polished, weakly striated planar to curviplanar surfaces. As reported in Caine and Minor (2009), some of these slip surfaces have rough groove and trough morphology. The clay-rich cores are generally thin with a median width of 3 cm (mean = 20 cm for n = 58 measurements; Fig. 11). Some of the faults have mixed zones and damage zones that are generally not well developed. Where there is “damage,” it usually consists of discrete deformation bands with short trace lengths. Most deformation bands are present within the damage and mixed zones, but not within the clay-rich fault cores. Very few joints were observed in the basin-fill sediments, particularly those that may be related to faulting.

### RESULTS FROM DATA ANALYSES AND MODELING

**Fault Types, Orientations, Kinematics, and Strain and Stress Models**

Within the eastern flanks of the Española Basin underlain by Proterozoic and Paleozoic rocks, thrust, reverse, strike-slip, and normal faults in rock (FIR) are all present; many of these show strong components of oblique slip. Figures 7, 8, and 12 show plots of all of the fault orientation data collected in these rocks. The data in these plots are organized by fault type and whether the fault slip surfaces are (1) principal slip surfaces (PSS) on major faults that bound fault cores or (2) minor slip surfaces (MSS) associated with major fault damage zones or single, isolated faults. It is also important to note that retro-deformation of the FIR data set to remove possible rotations from folding is not feasible because the data were collected in metaigneous and other metamorphic rocks.
Figure 12. Equal area, lower hemisphere projections of fault slip surfaces and slip vectors with associated best-fit, modeled strain (pink) and stress axes (blue), grouped by fault type and whether they are from faults in Proterozoic and Paleozoic rocks (FiR) or faults in poorly lithified basin-fill sediments (FiS; fault-slip data compiled from Minor et al. [2013] are shown in Figs. 12O–12R). T—extension axes; P—contraction axes; E2—intermediate Eigen vectors; \( \sigma_1, \sigma_2, \sigma_3 \)—maximum, intermediate, and minimum principal stress axes, respectively. Black and white arrows about the primitives are directions of maximum contraction (or compression) and maximum extension (or minimum compression), respectively. Slip vector arrows indicate motion of hanging wall, black great circles are principal slip surfaces (PSS), gray great circles are minor slip surfaces (MSS), and dashed red or pink great circles are PSSs and MSSs, respectively, that are incompatible with the strain or stress solutions shown. Strain models also show associated extensional (gray) and contractional (white) quadrants. Stress models also show green-brown–shaded contours representing areas of 95% confidence for each principal stress axis. Orientation and other numerical parameters for the strain and stress model results are shown in Table 2 and Table S1 (see footnote 1). ECE and SEE refer to general areas in east-central Española Basin and southeast Española Basin, respectively (see Fig. 2).
rocks lacking an original reference frame. Sites where data were collected from faults cutting both Proterozoic and Paleozoic rocks are in the hinge zones of open, upright folds where Paleozoic bedding is subhorizontal. The plots in Figure 12 show results from strain and stress modeling used to progressively group the faults into kinematically and mechanically compatible sets. There were no strain or stress model solutions that did not contain large numbers of misfits when all of the faults were analyzed together, when all of the reverse and strike-slip faults were analyzed together, or when any combination of normal fault subsets were analyzed together.

Reverse-slip and reverse-oblique-slip faults strike NWW to NE, are steeply to moderately dipping to the ESE, and are predominantly WNW directed (Figs. 12A and 12B). Thrust faults strike NW, are shallowly dipping to the SW, and are NE directed. Dextral and sinistral strike-slip faults form two dominant sets, NE and NW striking, respectively, both sets dipping steeply in either direction (Figs. 12C–12H). Normal and normal-oblique faults in rocks strike NNE to NE with opposing, quasi-conjugate, steep dips generally to the NW and SE (Figs. 12I–12N). In general, minor slip surfaces are similarly oriented and kinematically compatible with the principal slip surfaces for all fault types.

Fault data in the poorly lithified Tertiary basin-fill sediments (FiS; Figs. 12O–12R) of the Española Basin are compiled from Minor et al. (2013) and reorganized here to show data from geographically nearby locations relative to the FiR data (Figs. 12A–12N). Both regions where FiS were measured (Fig. 2; regions ECE and SEE) show NWW to NE fault strikes and steep dips to the WSW to WNW and ENE to ESE. Two dominant sets are apparent in each area that show opposing, quasi-conjugate geometry, and there is normal slip to normal oblique slip on each of these fault sets, but relative timing relations for the sets are uncertain. Although there is some overlap in orientation, the average conjugate bisectrices for the FiR have a NE trend compared with an approximately north trend for the FiS.

Model results for FiR PSS and MSS fault slip data show strain and paleostress coaxiality with WNW-ESE, subhorizontal best-fit shortening and maximum compression directions on reverse, reverse-oblique, and thrust faults with very few misfits (Figs. 12A and 12B). The best-fit strain results for all strike-slip faults are compatible with SW-NE subhorizontal shortening and a few misfits, however the strain and stress models do not produce comparable results (Figs. 12C and 12D). The strike-slip faults can be separated or deconvolved into two sets based on minimization of strain misfits, one dominated by NE-striking faults and the other dominated by NW-striking faults. Strain and stress models based on each of these subdivided fault sets produce comparable (i.e., coaxial) strain and stress results showing SSW-NNE and west-east subhorizontal shortening and maximum compression (Figs. 12E–12H).

Best-fit strain and stress models are dissimilar for all normal FiR with a minimum of misfits in each case (Figs. 12I and 12J). When these data are deconvolved into two sets based on minimization of strain misfits and independently based on minimization of stress misfits, two comparable strain and stress models emerge. One set is dominated by normal dip-slip faults (Figs. 12M and 12N) and the other dominated by normal oblique-slip faults (Figs. 12K and 12L). The set of normal dip-slip faults indicate NW-SE extension and minimum principal stress and the set of normal oblique-slip faults indicate NE-SW extension and minimum principal stress. In comparison, the FiS data produce comparable strain and stress models for both regions and show WNW-ESE extension and minimum principal stress (Figs. 12O–12R).

Aeromagnetic Data and Analysis of Basin-Scale Fault Length Data

Evaluation of the aeromagnetic data highlights magnetic lineaments consistent with field measurements of numerous generally north-striking, steeply dipping fault zones that cut the basin fill. Many more such fault zones are expressed in the aeromagnetic data than can be recognized from surface mapping alone (Figs. 5 and 6; Grauch and Hudson, 2007).

Table 1 shows the summary data for the fault populations and length distribution modeling results; the full data set can be found in Table S2 (see footnote 1). The total area of the aeromagnetic survey used in this analysis is ~6980 km² and contains a total of 575 uncensored intrabasin faults (Fig. 5). The fault lengths in each basin survey area span about three orders of magnitude, ranging from a minimum of 0.54 km to a maximum of 35.4 km with a median value of 3.3 km for all basins combined. The intrabasin fault intensities range from a minimum of 0.071 faults/km² in the Albuquerque Basin to a maximum of 0.106 faults/km² in the Española Basin, with individual domains of relatively higher-intensity faulting present within each basin. In the Española, two domains of relatively higher-intensity faulting are the Agua Fria and Barrancos zones (Figs. 2 and 6C; Grauch et al., 2009). Geophysical data indicate that the faults in these zones involve basement rocks, and kinematic data from field mapping in the faulted sediments indicate largely normal dip slip (Minor et al., 2013).

Although it is common to characterize a network of faults at the scale of single basins using trace length and displacement data, reliable displacement data for faults in the basin-fill sediments are only locally available (cf. Carter and Winter, 1999; Koning et al., 2013). However, the aeromagnetic data provide unique insight into fault characteristics from the trace length data alone. Aeromagnetically derived fault trace lengths were evaluated to determine whether systematic length distributions exist. The data were evaluated for all of the faults combined in the Española, Santo Domingo, and Albuquerque Basins as well as for each of the basins individually (Figs. 5 and 13).

There are a number of approaches for analyzing fault trace length data, and many indicate that such data exhibit a power-law distribution (e.g., Shaw and Gartner, 1986; Main et al., 1990; Davy, 1993; Cladouhos and Marrett, 1996; Nicol et al., 1996; Yielding et al., 1998; Cowie, 1998; Bonnet et al., 2001; Xu et al., 2010). A common approach is to plot fault length versus fault rank on a log-log plot and estimate the power-law exponent C using linear regression of an equation in the form:

\[ N = aL^{-C} \]
Figure 13. Plots of fault trace length versus fault rank (sequential order) derived from data shown in Figure 5, Table 1, and Table S2 (see footnote 1) from all basins (A) and from Albuquerque (B), Santo Domingo (C), and Española (D) Basins. In each log-log plot, a line described by a power-law function is fit to various proportions of the data. The equation and $R^2$ value for each fit is shown adjacent to each line using a coordinated color scheme.
where $L$ is fault length, $N$ is the ranked number of faults of length $\geq L$, and $a$ is a constant. The fitting approach used here was to plot all of the data and investigate the degree of fit using the root mean square error ($R^2$) for different proportions of the data and to evaluate the sensitivity for resulting values of $C$. The results show $R^2$ values between 0.84 and 0.90 for 100% of the data in all basins as well as in each individual basin with values of $C$ between 1.17 and 1.46 (Table 1). At $R^2$ of 0.95, values of $C$ are 1.14 for 88% of the data in the Española Basin, 1.16 for 72% of the data in the Santo Domingo Basin, and 1.22 for 86% of the data in the Albuquerque Basin. For all basins combined, the highest value of $C$ is 1.65 for 80% of the data at $R^2 = 0.95$ and $C = 1.33$ for 100% of lengths with $R^2 = 0.88$.

Goodness-of-fit tests indicate that the power-law function is a plausible fit of fault trace length distributions in the Española and Albuquerque Basins and data for all basins combined. Tests utilizing Kolmogorov-Smirnov statistics (KS test) generate $p$-values $>0.1$ if the power-law hypothesis is a plausible fit, otherwise it is rejected (Clauset et al., 2009). KS test $p$-values are $>0.1$ in the Española and Albuquerque Basins and all basins combined, but are $<0.1$ in the Santo Domingo Basin (Table 1). A likelihood ratio test directly compares the power-law hypothesis with an alternative such as an exponential or lognormal function. The test calculates a likelihood statistic for two competing functions, and then calculates the ratio ($R$) of the two likelihoods, which is positive or negative depending on which function is favored (Clauset et al., 2009). In this case, positive $R$ indicates that the power law is favored over the competing function. Data from the Albuquerque Basin and all basins combined favor a power-law fit, Santo Domingo Basin data favor a lognormal function, and Española Basin data can be about equally well fit by a power-law or lognormal function (Table 1). Goodness-of-fit tests confirm that the power-law hypothesis is appropriate for the fault trace length data in the Española and Albuquerque Basins and all basins combined, however the data retrieved from the Santo Domingo Basin are best modeled by a lognormal function.

**Mineralogy of Fault Zones and Breccia Bodies**

Figures 14 and 15 show box plots of representative whole-rock, semi-quantitative mineralogy data from each of the temporal rock groupings, with major rock-forming and clay minerals organized by fault zone component or rock type.

**Faults Involving Proterozoic Rocks**

For Proterozoic fault core rocks compared with their protoliths, there are no statistically significant differences between the median concentrations for any of the major rock-forming minerals ($U$ and $p$ values at 95% confidence). However, the variability in concentrations marked by the span of the 75th and 25th percentiles is generally higher in the fault core rocks compared with the protoliths, but the bounds of the protolith variability are generally contained within that of the cores. The largest variations between protoliths and cores are in plagioclase, total clays (sum of all clay minerals), and ferromagnesian minerals. When looking at specific clay mineral changes, median illite concentrations are over 10x greater and median smectite concentrations 6x greater in the fault core rocks compared with their protoliths (Fig. 15). The variation in illite and smectite concentrations is also much greater in the fault cores than in the protoliths. It is notable that kaolin is only found, albeit in low concentrations, in the damage zones and fault core rocks.

Proterozoic damage zone samples are only from the Hyde Park Road fault and Santa Fe fault, and these samples shows significantly higher medians and variation in total clay compared with the protoliths. Damage zone illite, smectite, and kaolin median concentrations and variability are statistically significant and all greater than in the protoliths (Fig. 15). In the damage zone samples, potassium feldspars are more variable than in the protoliths, and plagioclase has been destroyed completely (Fig. 14). This is consistent with thin-section and field observations that indicate argillic hydrothermal alteration that preferentially converted plagioclase to sericite and clay (Fig. 10). Concentration variations of ferromagnesian minerals are lower for all fault zone components compared with protoliths.

Significantly, mineralogical changes and variations in the breccias differ the least compared with their protoliths, and breccias are unlike any of the fault core rocks (Figs. 14 and 15). This is true for samples from breccias hosted in either granitic or amphibolitic protoliths, with the exception that the ferromagnesian minerals show less variation in both protoliths. The breccias do show statistically significant differences from the damage zones for quartz, plagioclase, and total clay. Median illite concentration is ~5x greater, and median kaolin concentration ~2x greater, in the damage zones compared with the breccias (Fig. 15). These differences are largely due to changes in the damage zones, not the breccias.

**Faults Involving Proterozoic and Paleozoic Rocks**

Variations in all mineral concentrations of faults involved with Paleozoic and Proterozoic rocks are large (Fig. 14). However, none show statistically significant differences in median concentrations except for an increase in total clay and the nearly complete absence of calcite from the fault core rocks. Clay mineral-specific changes show nearly 8x more illite in the Paleozoic damage zone samples compared with the protoliths and 30x more kaolin in the fault core rocks versus the protoliths (Fig. 15).

**Faults Involving Tertiary Sediments**

In faults cutting Tertiary sediments, samples of calcite-cemented and uncemented protoliths are compared with the fault core rocks. There is twice as much median quartz (and more variability in quartz) and median potassium feldspar in the uncemented protoliths as in the cores (Fig. 14). There also is about twice as much median plagioclase in the cemented protoliths as in the cores.
Figure 14. Box plots of major rock forming mineral concentrations from X-ray diffraction for Proterozoic (greens) and Paleozoic (blues) rocks and Tertiary sediments (yellows and reds), grouped by fault zone component. Each box shows the concentrations of the 75th percentile (top box edge), the median (intermediate line), and 25th percentile (bottom box edge) for each component. The top and bottom whiskers show the concentrations of the 90th and 10th percentiles, respectively. The number of samples in each component are: Proterozoic protoliths (PLs) = 6; Proterozoic damage zones (DZs) = 5; Proterozoic cores = 6; Proterozoic breccias = 7; Paleozoic PLs = 4; Paleozoic DZs = 6; Paleozoic cores = 3; Tertiary uncemented (uc) PLs = 16; Tertiary cemented (c) PLs = 5; Tertiary cores = 15. The numeric value for the factor of exceedance between the indicated component medians that have statistical significance at 95% confidence is shown below each respective box (BXA—breccia; FR—fault rocks).
Figure 15. Box plots of clay mineral concentrations from X-ray diffraction for Proterozoic (greens) and Paleozoic (blues) rocks and Tertiary sediments (yellows and reds), grouped by fault zone component. Each box shows the concentrations of the 75th percentile (top box edge), the median (intermediate line), and 25th percentile (bottom box edge) for each component. The top and bottom whiskers show the concentrations of the 90th and 10th percentiles, respectively. The number of samples in each component are Proterozoic protoliths (PLs) = 6; Proterozoic damage zones (DZs) = 5; Proterozoic cores = 6; Proterozoic breccias = 7; Paleozoic PLs = 4; Paleozoic DZs = 6; Paleozoic cores = 3; Tertiary uncemented (uc) PLs = 16; Tertiary cemented (c) PLs = 5; Tertiary cores = 15. The numeric value for the factor of exceedance between the indicated component medians that have statistical significance at 95% confidence are shown below each respective box (BXA—breccia; FR—fault rocks).
Uncemented protolith medians have about twice as much total clay as the cemented protoliths, and the fault core rocks have 2.5x and 4.3x more total median clay and greater variability than the un Cemented and cemented protoliths, respectively. Calcite median concentrations are 27x greater in the cemented protoliths compared with the un Cemented protoliths, and 30x greater in the cemented protoliths compared with the fault core rocks, which are essentially the same as the un Cemented protoliths with respect to median calcite concentrations (Fig. 14). Tertiary fault clays are rich in muscovite (detrital?), illite, and smectite, and all show large variabilities compared with the protoliths. Median chlorite is 2–4× greater in the fault core clays compared with un Cemented and cemented protoliths, respectively, and is twice as great in the un Cemented versus cemented protoliths.

**Elemental Chemistry of Fault Zones and Breccia Bodies**

Figures 16–23 show all elemental chemistry data. Figures 16–17 and 20–23 show box plots of major, trace, and rare earth element concentrations for representative samples of protoliths, damage zones, fault rocks, and breccias. To facilitate comparisons among the different age and protolith rock type groupings, envelopes are drawn around the 75th and 25th percentiles for a number of combinations of the various rock type components presented.

**Faults Involving Proterozoic Rocks**

Fault core rocks in faults involving Proterozoic rocks, compared to their protoliths, show few statistically significant differences in median values and small variations in the concentrations of major, trace, and rare earth elements. Barium is the one exception, where its concentration is ~2x smaller in the fault rocks compared with the protoliths (Fig. 16). Damage zones compared with protoliths and fault rocks do show differences; Rb, Cu, Cs, and W show statistically significant higher concentrations (up to 6 greater) compared with protoliths. Greater variability of damage zone versus fault rock concentrations of Fe, Ti, P, Mn, Ba, Sr, Zn, Cr, Ni, Cu, and Th are also notable.

**Breccias Involving Proterozoic Rocks**

Breccias in Proterozoic rocks show remarkably few median changes or variability in elemental chemistry compared with their protoliths (Fig. 17). The exception is the statistically significant median for W that is 3x higher than in the protoliths. Conversely, the increased variation among Proterozoic breccias and fault core rocks is notable particularly for Ca, Mg, Ti, Mn, V, Cr, Ni, Co, Cs, W, La, and Ce.

Given the proximity of the enigmatic breccias in the Proterozoic basement rocks to known shatter cones, separate and high-resolution instrumental neutron activation analysis (INAA) was conducted to determine if anomalous iridium, chromium, and nickel are present in any of the brec ciated rocks. Iridium is one of the rarest elements in the Earth's crust, with median concentrations on the order of 0.04 ppb (GERM, 2014). However, Ir is commonly found in association with meteorites and associated impactites (Tagle and Hecht, 2006; Tagle and Berlin, 2008; Koeberl et al., 2012). Iridium and its geochemical behavior with respect to Cr and Ni provide possible clues to whether the breccias are associated with the impact-related shatter cones.

Figure 18 shows box plots of measured Ir concentrations for average continental upper crust, protolith samples, breccia clasts and matrix, clasts alone, matrix alone, fault-related breccias, and individual slip surfaces that cut breccias. Rank sum analysis as completed for the ICP-MS major, trace, and rare earth element data shows that samples of breccia clasts plus matrix have statistically significant higher median concentrations and variability of Ir compared with the protolith samples. The breccia clasts plus matrix show median Ir concentrations 4.1x and 10.4x greater than protoliths and average crust, respectively (Fig. 18). Median concentrations of breccia clasts alone, fault breccias, and slip surfaces are also elevated relative to the protoliths and crust, and the protolith median is 2.5x greater than that of the crust. The median of the breccia matrix alone is not statistically different than that of the breccia clasts plus matrix, and its variation is the second highest of the groupings.

Figure 19 shows scatter plots of Cr and Ni versus Ir. Median, maximum, and minimum values of chondritic meteorites, a variety of impactites, average upper continental crust (UCC), and the groupings for the Española protoliths and breccias are shown. All groups are shown on log-log plots to show the full spread of available data, and most of the Española data are shown as insets using a linear scale to show detailed relations. The chondrites, impactites, and UCC form a mixing line used to discriminate mixtures of extraterrestrial versus terrestrial end-member samples that are involved with impacts (Morgan et al., 1975; Tagle and Hecht, 2006; Tagle and Berlin, 2008). The Española breccia data show elevated Ir comparable with some impactites and with respect to both Cr and Ni, but lower values of both Cr and Ni relative to impactites and UCC (Fig. 19). Some protolith Cr and Ni values are comparable to or elevated with respect to those of UCC and the impactite mixing line and are also all elevated in Ir concentrations.

**Faults Involving Proterozoic and Paleozoic Rocks**

Faults involving Paleozoic rocks show statistically significant median reductions in fault core rocks compared with protoliths in Rb, Co, Cs, and U and in damage zones compared with protoliths in Co, Cs, Dy, and Ho (Fig. 20). In general, most elements show more variability in protoliths compared with cores and in damage zones compared with cores showing that Ca, Nd, Sm, Eu, and Gd are notably elevated.
Figure 16. Box plots of elemental concentrations from the Santa Fe Mountains rift flank Proterozoic protoliths (PL, olive green) and fault rocks within them (FR, light-olive green). Each box shows the concentrations of the 75th percentile (top box edge), the median (intermediate line), and 25th percentile (bottom box edge) for each component. The light yellow-green shaded envelopes encompass the 75th and 25th percentiles of PL-FR pairs, and the light green envelopes, PL-DZ (damage zone) pairs. The top and bottom whiskers show the concentrations of the 90th and 10th percentiles, respectively. Unless otherwise noted below the element column, the numbers of samples (n) are PL = 8, DZ = 5, and FR = 7 in the major and trace element and trace element plots, and PL = 7, DZ = 5, and FR = 7 in the rare earth element plot. The numeric value for the factor of exceedance between the indicated component medians that have statistical significance at 95% confidence are shown in bold below each element symbol.
Figure 17. Box plots of elemental chemistry from the Santa Fe Mountains rift flank Proterozoic protoliths (PL, olive green) and non-fault-related breccias within them (BXA, light brown). Box plot percentile demarcations, envelopes (PL-BXA, beige; PL-FR [fault rocks], light green), and significant exceedances are the same as for Figure 16. Unless otherwise noted below the element column, the numbers of samples (n) are PL = 8 and BXA = 16 in all plots.
Faults Involving Tertiary Sediments

The most notable overall chemical changes that are statistically significant with respect to the median concentrations are found in faults associated with Tertiary sediments (Fig. 21). With respect to un cemented protoliths, fault core samples show generally ~2x increases in Fe, Mg, Ti, V, Cr, Zn, Ni, Cu, Co, and Cs. With respect to calcite cemented protoliths, fault cores show increases in Al, Ca (10.5x), Mg, Ti, P, V, Cr, Rb, Zn, Cu, Th, Cs, W, La, and Ce. Uncemented versus calcite cemented protoliths show significantly different variations in Ca, Mg, V, Cr, W, and possibly Ce.

Comparisons of Faults Involving Proterozoic, Paleozoic, and Tertiary Rocks and Sediments

All variation envelopes for Proterozoic, Paleozoic, and Tertiary protoliths and fault core samples are extracted and overlapped for comparison in Figure 22. For most elements, the concentration variations of the three temporal and rock type groupings track one another with some notable differences. Faults involving Paleozoic rocks show Al, K, Ti, Ba, Sr, Zr, Rb, Th, La, and Ce concentration variability that overlaps that of the protolith samples and larger low-end ranges compared with Proterozoic and Tertiary samples. Paleozoic protoliths show greater concentration variabilities of Ca, Mn, Li, and Pb compared with Proterozoic and Tertiary protoliths. Sr, Li, Pb, and U concentration variations are elevated in Paleozoic fault core samples compared with Proterozoic and Tertiary samples. Proterozoic protolith and fault core sample variations are elevated in K, Rb, and the heavy rare earth elements compared with Paleo zoi c and Tertiary sample variations. Tertiary fault core sample variations show minor but relatively more Mg, Mn, and Ba and relatively less Ni, Th, Cs, U, and the heavy rare earth elements compared with Proterozoic and Paleozoic sample variations.

Figure 23 shows the distribution of elemental chemistry in calcite veins that cut Proterozoic and Paleozoic rocks and Tertiary sediments. Although rank sum analyses were not run for these vein samples, in general, median values are similar among most groups for most elements with the exceptions of Al, K, Ti, Mn, Zr, Rb, Th, and Ce. Median values for veins in Proterozoic and Paleozoic rocks tend to be lower in these elements compared with the veins in Tertiary sediments. Qualitatively, variability for most elements are similar for veins in most of the groups, except for Mn, Zr, V, Ni, Co, Pb, Th, and W in Paleozoic rocks; Ca, Mg, P, Cr, Rb, Zn, Cu, Cs, Nd, Sm, and Eu in Tertiary sediments; Co, Th, W, and Lu, which are notably more variable in veins in Proterozoic rocks compared with Paleozoic rocks and Tertiary sediments.

INTERPRETATIONS

Characteristics of Española Faults and Breccias and Their Possible Influences on Groundwater Resources

The geological compilation map of the eastern Española Basin shows the geologic, structural, and geomorphic framework that hosts groundwater in a faulted and exhumed crystalline mountain block juxtaposed against a rift basin filled with poorly lithified sediments (Figs. 2 and 4). Unlike similar range fronts such as the Sangre de Cristo in the eastern San Luis Basin of Colorado (Huntley, 1979) or the Wasatch in the eastern Great Salt Lake Basin of Utah (Manning and Solomon, 2003), the mountain front of the Santa Fe Mountains along the eastern flank of the Española Basin is not characterized by a continuous, large-displacement normal fault. Although faults mapped and observed along the Santa Fe mountain front do have clay-rich gouge in their cores, their discontinuous nature suggests that they are at most partial barriers to mountain block recharge (MBR) into the Española Basin. Additionally, there is a number of steeply dipping, long-trace-length, NE-striking faults with fractured damage zones, as well as a prominent steeply dipping and NE-striking pervasive joint set, whose orientations are subparallel to the mean topographic and hydraulic gradient (Fig. 4).

Several geologic observations suggest that the fractured, crystalline mountain block is an unconfined aquifer able to recharge water to the basin in the...
subsurface, including: (1) Manning (2009) showed that noble-gas recharge temperatures indicate significant MBR to basin aquifers; and (2) Johnson et al. (2013) showed that there are no gradients in groundwater elevation, temperature, or chemistry at the relatively shallow break in slope between the mountains and basin. Within the Española crystalline aquifer, fault-related and other breccia bodies are of small to relatively moderate size (e.g., Fig. 4). These bodies may be local heterogeneities in terms of shape and permeability but are currently not likely aquifers themselves. Based on observations of local pore-filling calcite, the larger breccia bodies may have once been of locally higher permeability than their surrounding unbrecciated host rocks, and thus may have been important for limited groundwater storage. They may also have been important for groundwater flow within the relatively low-permeability bedrock aquifer, particularly where they may have been in direct contact with basin-fill sediments in the subsurface.

Within the sediments of the Española Basin there are a number of long-trace-length fault zones and complex zones of high-intensity faulting that do have physical and geochemical impacts on the basin-scale groundwater flow system (Figs. 4, 5, and 6). Such impacts include local aquifer compartmentalization of flow and recharge, focusing flow from and to crystalline basement rocks, and localization of groundwater and rock geochemical anomalies. Two zones are particularly notable in the Española study area: the Agua Fria fault system that includes the San Isidro Crossing fault, which coincides with a large drop in the water table elevation, and the Barrancos fault system that is correlated with groundwater chemical and thermal anomalies (Fig. 2; Grauch et al., 2009; Manning, 2009; Johnson et al., 2013). Although the intrabasin faults found in these zones have well-developed clay-rich gouge fault cores and mixed zones, they do not have well-developed damage zones composed of open fractures (e.g., Fig. 8). This suggests that the chemical and thermal anomalies are caused by anisotropic groundwater flow along the permeability contrast of the clay-rich gouge fault cores within the siliciclastic sediments alone (Rawling et al., 2001; Bense and Person, 2006; Caine and Minor, 2009).
Figure 20. Box plots of elemental concentrations from the Santa Fe Mountains rift flank Paleozoic protoliths (PL, dark blue) and fault rocks within them (FR, light blue). Box plot percentile demarcations, envelopes (PL-FR, powder blue; PL-DZ (damage zone), light gray-blue), and significant exceedances are the same as for Figure 16. Unless otherwise noted below the element column, the numbers of samples (n) are PL = 8 and FR = 9 in the major element and trace and trace element plots, and PL = 7 and FR = 4 in the rare earth element plot.
Figure 21. Box plots of elemental concentrations from the Santa Fe Mountains rift flank Tertiary uncremented sediment protoliths (PL, beige) and fault rocks within them (FR, maroon). Box plot percentile demarcations and significant exceedances are the same as for Figure 16. The salmon shaded envelopes encompass the 75th and 25th percentiles of uncremented (uc) PL uncremented (uc)-FR pairs, and the yellow envelopes, the PL cemented (c)-FR pairs. The numbers of samples (n) are PLuc = 38, PLc = 30, and FR = 10 in the major and trace element and trace element plots, and PLuc = 12, PLc = 5, and FR = 19 in the rare earth element plot. Numbers in parentheses below element columns indicate different numbers of samples than reported above for PLuc, PLc, and FR.
Figure 22. Box-plot envelopes for Proterozoic (PC, beige, Fig. 16), Paleozoic (PZ, blue, Fig. 20), and Tertiary (T, red, Fig. 21) protoliths (PL) paired with fault rocks (FR) within them. Each envelope is pinned to the midpoint of the 75th percentile (top of each envelope) and 25th percentile (bottom of each envelope) for each component.
Figure 23. Box plots of elemental concentrations from the Santa Fe Mountains rift flank calcite veins in Proterozoic (PC, light green), Paleozoic (PZ, light blue), and Tertiary (T, beige) fault-related rock and sediment protoliths. Box plot percentile demarcations are the same as for Figure 16. Unless otherwise noted below the element column, the numbers of samples (n) are Proterozoic = 5 in the major and trace element and trace element plots, and 3 in the rare earth element plot; Paleozoic = 4 in all plots; Tertiary = 9 in the major and trace element and trace element plots, and 5 in the rare earth element plot.

Proterozoic, Paleozoic, and Tertiary Calcite Veins

Major and Trace Elements

Trace Elements

Rare Earth Elements
Kinematic and Paleostress Analyses

Fault kinematic models for faults in Proterozoic and Paleozoic rocks show WNW-ESE, subhorizontal shortening on compatible WNW-directed reverse and reverse-oblique faults and NE-directed thrust faults with very few misfits (Table 2; Figs. 12A and 12B). From the framework of an Andersonian mechanical model, only a subset of the dextral and sinistral strike-slip faults observed in these rocks is directly compatible with WNW-ESE, subhorizontal shortening (Figs. 12G and 12H). The remaining, dominantly NE-striking subset of dextral and sinistral strike-slip faults is compatible with SW-NE subhorizontal shortening that is nearly 90° from the WNW-ESE shortening model related to contractional faults (Figs. 12E and 12F). Some of the opening-mode joint sets also are compatible with each of these shortening directions (Fig. 8).

There was no observed field-based relative or absolute age information among the Española reverse, thrust, and strike-slip fault data. Erslev (2001) was able to measure fault slip, complete paleostress analyses, and interpret results from various units in north-central New Mexico that span ages from Caine et al. | Survey of brittle structures, Rio Grande rift, New Mexico

TABLE 2. STRAIN AND STRESS MODEL RESULTS

<table>
<thead>
<tr>
<th>Fault type</th>
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<th>Faults in sediment</th>
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<td>12/16</td>
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<tr>
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<td>θ</td>
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Note: Plot number refers to individual plots A–R in Figure 12.

Abbreviations: n—number of data used; n0—total data; PSS—number of primary slip surfaces; MSS—number of minor slip surfaces; P—contractional axis; T—extensional axis; Decon.—deconvolved model; ECE—east-central Española Basin; SEE—southeast Española Basin; σ1, σ2, σ3—maximum, intermediate, and minimum principal stress axes; φ—stress ratio; θ—mean misfit fault angle; θ—mean fault angle with model maximum shear stress direction.
Field observations of cross-cutting relations and the FiR slip data from the flanks of the Española Basin do provide good constraints to indicate that normal faulting occurred after contractional and strike-slip faulting and that maximum horizontal extension was dominantly NW-SE (Table 2; Figs. 12M and 12N). The strain and stress models for all FiR normal faults show nearly identical vertical P and σ1 axes, however T and σ3 axes are ~90° from one another (Figs. 12I and 12J). The full normal FiR data set is composed of both oblique-normal faults, with dextral and sinistral components, and pure normal-slip faults. Separate models computed from these two normal fault subsets have nearly coaxial strain and paleostress indicating SW-NE extension and minimum principal stress (normal oblique-slip faults) and SE-NW extension and minimum principal stress (normal dip-slip faults), both with vertical P and σ1 axes. Interpretation of the SW-NE extension is inconclusive, but could have resulted from extensional collapse during the waning stages of the Laramide orogeny and/or reflect early-rift far-field SW-NE extension inferred by Zoback et al. (1981). The normal oblique-slip FiR compatible with the SW-NE T and σ3 axes are consistent with reactivation of preexisting NE-striking, possibly Laramide-age faults (Figs. 12K and 12L).

Another possibility is that there was sufficient strength anisotropy in the rift flank due to preexisting Laramide brittle faults and that the transition to rifting was marked by reactivation of these structures. The strain model for all of the normal faults only shows two misfits on NW-striking faults. The consistent NE strikes of the remaining, well-fit normal faults may be influenced by preexisting NE-striking contractional and strike-slip structures (Fig. 12). In addition, there is direct and indirect evidence that the extensional slip reactivated both major and minor structures of possible Laramide age. Such evidence includes co-location and co-orientation (cf. Caine et al., 2010) of reverse and strike-slip faults with major and minor normal faults and associated structures. However, no evidence was found to indicate reactivation of Proterozoic mylonitic structures, folds, or foliations. For example, compositional layering in Proterozoic hanging-wall metasedimentary rocks is nearly at right angles to the Santa Fe fault, not a favorable configuration for reactivation of the local Proterozoic fabrics.

Results of the strain and stress analyses for the Española Basin based on the FiS data from Minor et al. (2013) indicate WNW-ESE-trending extension and minimum principal stress axes for both strain and stress models in latest Oligocene through late Miocene basin-fill sediments (Table 2; Figs. 12O–12R). This extension direction is consistent with a variety of models for mid- to late-rift, far-field regional stress indicative of west-east to WNW-ESE extension (e.g., Zoback et al., 1981; Erslev, 2001; Minor et al., 2013). In the central and southern Española Basin, normal and normal-oblique faults are dominantly north-south striking, but range from NNW to NNE strikes, and a few NE-striking faults also exist (Fig. 12). In contrast, most of the normal FiR in Proterozoic and Paleozoic rift flank rocks strike NE and indicate mid- to late-rift NW extension; thus, north-south–striking normal faults are underrepresented in the FiR compared with the FiS.

There are a few possible scenarios to explain the differences in fault strikes and modeled extension directions between FiR and FiS. WNW-ESE extension associated with north-south–striking normal faults within the Española Basin sediments may not have been accommodated by similar faults in the exhuming rift-flanking basement rocks, perhaps influenced by bulk strength contrasts between these very different materials. In this scenario, the NE-striking normal FiR would be older structures that accommodated earlier NW extension (e.g., Fig. 12I). Alternatively, differences in modeled extension directions may reflect reactivation of basement rocks controlled by strong, steeply dipping, NE-striking brittle strength anisotropy in comparison with development of new faults in relatively weak, nearly isotropic basin sediments perhaps more sensitive to regional, far-field WNW-ESE extension. In contrast to the first scenario, here the NE-striking normal FiR and approximately north-striking FiS (and their respective extension directions) would be coeval. Most of the extensional FiR show generally dip slip rather than oblique slip as might be expected if the FiR were older and later reactivated during far-field WNW-ESE extension, also consistent with local spatial changes in the stress field.

**Trace Length Distributions of Intrabasin Faults**

Aeromagnetic data reveal buried faults and allow for the measurement of the length of their magnetic lineaments as a proxy for fault length, and thus provide a unique assessment of the nature of fault length distributions and fault growth in tectonically linked basins of the Rio Grande rift. Based on numerical modeling by Cladouhos and Marrett (1996) and Xu et al. (2010), values of the power-law exponent C have been shown to generally decrease with increasing growth by fault linkage. Fault growth may also reflect strain localization where progressive deformation over time leads to fewer, but longer and weaker, hand-linked faults (Walsh et al., 2003). Values of the power-law exponent C in Equation 1 that fit central Rio Grande rift intrabasin fault trace length data at $R^2 = 0.95$ range from 1.14 to 1.22 for individual basins and 1.65 for all basins combined (Fig. 13; Table 1). These values are well within the range reported in the literature, where $C$ ranges from 0.60 to 2.07 when estimated from all distributions, and from 0.61 to 2.07 when estimated from fault length versus fault rank plots (Cladouhos and Marrett, 1996; Yielding et al., 1996; Bonnet et al., 2001; Xu et al., 2010). However, at $R^2 = 0.95$, the percentages of the data that fit a power-law distribution are between 72% and 88% for each individual basin and 80% for all basins combined. The values of $C$ for the three basins studied here do get slightly larger with increasing basin size, but do so with a very flat slope suggesting relative insensitivity of $C$ to basin size over the range of fault lengths sampled, from ~0.5 km to ~35 km (Fig. 13). Figures 5 and 6 show the mapped distribution of fault locations, and it can be seen that both long and short subparallel faults are for the most part evenly distributed throughout each basin.

Faults of intermediate length within each central Rio Grande rift basin are consistent with power-law or lognormal distributions spanning ~2.5–3 orders of length magnitude. Relatively low values of $C$ for a broad range of possible least-square power-law fits in central Rio Grande rift basins, field observations
of linked faults, and the presence of long and short subparallel faults that are evenly distributed throughout each basin indicate that fault growth by linkage appears to be an important process in the extensional evolution of the central Rio Grande rift fault network within all three basins.

Aeromagnetically derived fault length data provide a unique view of fault length distributions. Understanding of fault length distributions has previously come from detailed outcrop measurements, regional geological mapping, seismic data, and numerical modeling. The results presented here from analyses of aeromagnetically derived fault length data are consistent with distributions from many other areas globally and derived from a number of measurement sources. It also is noteworthy that C values for central Rio Grande rift basins reflect fault length distributions in poorly lithified sediments, some with evidence of growth faulting. These data match reported C values (Cladouhos and Marrett, 1996; Xu et al., 2010) in a large variety of well-indurated sedimentary rocks, some with growth faulting, as well as in volcanic rocks. This supports the inference that fault growth by linkage is a fundamental process in the evolution of deformation in the Earth’s upper crust irrespective of the degree of induration of the geologic medium.

Fault Zone Mineralogy and Elemental Geochemistry

In faults on the east flank of the Española Basin that primarily cut Proterozoic rocks, the characteristic mineralogical signature is the development of clay in fault cores and damage zones interpreted to largely be at the expense of plagioclase feldspar (Fig. 14; cf. Evans, 1990; Evans and Chester, 1995). Thin sections show evidence for intermediate argillaceous hydrothermal alteration preferentially concentrated in plagioclase grains from fault damage zones (Fig. 10). Evidence for silicification was only found in the western Santa Fe fault locality and is lacking in any other fault-related rocks of any age grouping. Interestingly, the concentrations of major elements such as Al, Fe, Ca, K, Ti, P, and Mn are all relatively unchanged in fault cores relative to their protoliths in Proterozoic rocks. Damage zones also show no statistically significant changes in the concentrations of these elements relative to protoliths but do show larger variations relative to the fault cores. Such a lack of change in lithophile ion concentrations in comparison to clear mineralogical changes suggests that for most faults the bulk transformation from feldspar to clay was largely isochronous among protoliths, damage zones, and fault cores in the Proterozoic rocks (cf. Eichhubl et al., 2005).

However, there are a few trace elements, Rb, Cu, Cs, and W, mainly in the fault damage zones that show statistically significant enrichments from protolith concentrations (Fig. 16). Higher fracture intensities observed in damage zones of the faults dominantly in Proterozoic rocks are consistent with at least transiently high permeability and the focusing of hydrothermal fluids in such zones. Such alteration focused in the damage zones is also an indicator of past fluid (and possibly vapor) flow. Flow and associated reactions would appear to have caused open-system, selective mobility of some trace elements in the higher-permeability fractured damage zones compared with the lower-permeability fault cores that are rich in clay minerals with few hydraulically conductive fractures except perhaps when the faults were actively deforming (cf. Goddard and Evans, 1995).

Interestingly, the clay-rich fault gouges clearly cut the damage zone rocks and contain visible cataclastic fragments of the hydrothermally altered damage zone materials within them (Figs. 9H and 10B). This suggests that early, bulk hydrothermal alteration in the incipient fault zones was important in localizing progressive strain by argillic weakening (cf. Caine et al., 2010; Bacekberg et al., 2016). Fault zone architecture likely evolved from zones of distributed fracturing to composite deformation zones with well-developed younger fault cores surrounded by older damage and alteration zones. As deformation progressed, strain became more highly localized in the core where a full array of clay minerals was both inherited from the damage zone as well as newly grown. The lack of more than one observed fault core in each fault zone is evidence that this strain localization persisted through the rest of the deformation history of faulting. Fault core-related breccias show evidence of multiple brecciation events where clasts are internally altered and the internal sericite and illite grains show different extinction angles than those in the surrounding matrix (Fig. 10). This observation also is consistent with early hydrothermal alteration in a layer of multiple strain localization and fault core growth. Progressive fault-related hydrothermal fluid flow presumably occurred during the Laramide orogeny and continued during the formation of the Rio Grande rift because reverse, strike-slip, and normal faults all show evidence for argillaceous alteration.

There are clear signs of protolith compositional control on damage zone and fault core mineralogy. The Proterozoic, largely granitic protoliths dominantly produced illite fault rocks, whereas the Paleozoic sedimentary rocks composed of interlayered sandstones, shales, and carbonates produced fault rocks dominated by kaolin and smectite, and the dominantly siliciclastic and volcaniclastic Tertiary basin-fill sediments produced fault cores dominated by smectite and illite (Fig. 15). These clay mineral signatures can be tied to: (1) the abundance of potassium and plagioclase feldspars in Proterozoic granitic rocks that tend to react to illite under hydrothermal conditions; (2) the abundance of shale in the Paleozoic rocks that commonly contain detrital kaolin; and (3) weathering of volcanic clasts in basin fill to form smectite-dominated clay mineral assemblages entrained in the fault cores.

Calcite shows small concentrations in fault cores of faults in all protoliths and age groupings (Fig. 14). Relative to Paleozoic protoliths, calcite appears to have been depleted in fault cores, and relative to Tertiary protoliths, calcite appears to have remained largely unchanged in fault cores. Calcite veins are most abundant in faults dominantly within Paleozoic protoliths but are also present in Proterozoic faults and breccias and Tertiary faults. The variations in elemental chemistry of calcite veins in each fault-related age grouping (Fig. 23) are not large but presumably reflect influences of the protoliths and source reservoirs. Ferromagnesian minerals, predominantly biotite and hornblende, show no statistically significant change in any rock grouping except that the protoliths
of the Proterozoic rocks have the highest variability compared among all fault components and age groupings. This is consistent with relatively low-grade hydrothermal alteration suggesting minimal liberation and transport of Fe, Mg, and other associated elements in these refractory minerals.

**Geochemistry and Origins of the Enigmatic Breccias as Possible Impactites**

Enigmatic, non-fault-core breccias in Proterozoic rocks show remarkably few mineralogical or elemental chemical changes relative to their protoliths (Figs. 14, 15, and 17). This is consistent with their characteristic texture being autoclastic, without incorporation of far-traveled exotic materials. Anomalous geochemical enrichments in iridium were found in non-fault-core breccias and associated protoliths, slightly above UCC and comparable to some impactites (Figs. 18 and 19). However, values of chromium and nickel, commonly used in combination with iridium as a discriminant for extraterrestrial sources, are depleted relative to UCC and impactites. Española breccias near faults show evidence for low-grade argilllic hydrothermal alteration consistent with low-pH fluids. Although the solubility, mobility, kinetics, and speciation of Ir, Cr, and Ni in the near-surface environment of the Earth are poorly understood, they are leachable and can be mobilized under certain conditions, but Cr and Ni are strongly sorbed by Fe- and Mn-oxides (Gray, 2003; Massoura et al., 2006; Martin-Peinado and Rodríguez-Tovar, 2010; Raous et al., 2010). For the observed selective depletion of Cr and Ni, relative to Ir, to have occurred, exposure to low-pH waters may have been an important process. It is unclear how or when this may have happened, but there is thin-section evidence that there was late replacement of pore-filling fluids by unstrained calcite after iron hydroxides were deposited (Fig. 10F).

The age of non-fault-core brecciation is poorly constrained, but likely occurred after the Paleoproterozoic (Fackelman et al., 2008) and prior to Pennsylvanian time. This is based on map and outcrop observations showing Pennsylvanian carbonates in depositional contact over brecciated and unbrecciated Proterozoic rocks and that subrounded boulders of brecciated Proterozoic rocks are deposited within the carbonates at one locality (cf. McElvain et al., 2006; Caine et al., 2007; Fackelman et al., 2008; Tegtmeier et al., 2008). Consistent with these field-based timing observations, brecciation is thus not related to Laramide folding or rift-related extension, but tectonic processes during Pennsylvanian time. This is based on map and outcrop observations showing Pennsylvanian carbonates in depositional contact over brecciated and unbrecciated Proterozoic rocks and that subrounded boulders of brecciated Proterozoic rocks are deposited within the carbonates at one locality (cf. McElvain et al., 2006; Caine et al., 2007; Fackelman et al., 2008; Tegtmeier et al., 2008). Consistent with these field-based timing observations, brecciation is thus not related to Laramide folding or rift-related extension, but tectonic processes during Pennsylvanian time. This is consistent with relatively low-grade hydrothermal alteration suggesting minimal liberation and transport of Fe, Mg, and other associated elements in these refractory minerals.

Conclusions

Although inconclusive and circumstantial, the available evidence does not rule out an impact-related origin for the Española breccias. The evidence includes: proximity to and same structural elevation as known shatter cones; arcuate outcrop pattern of the shatter cones, possibly near potential foci; irregular shapes of many of the breccia bodies, particularly those that have dike-like geometries suggestive of injection; microscopic evidence of injective flow of particles in breccia-related veins; highly angular autoclastic, single-event textures; and anomalously elevated iridium concentrations in the breccia clasts and matrix and adjacent Proterozoic protoliths. The breccia bodies are clearly distinct from fault-related breccias such as those found in the Santa Fe fault, which are bound by slip surfaces rather than being cut by them and are confined to fault zones.

**DISCUSSION**

**Significance of Structural Geologic Heterogeneities on Groundwater Resources**

Crystalline mountain blocks juxtaposed with poorly consolidated basin-fill aquifers, whether fault bounded or not, are a common geological and topographic configuration in the intermountain western United States (e.g., Huntley, 1979; Keating et al., 2003; Manning, 2009). This configuration allows for the orographic capture of precipitation and subsequent runoff and/or groundwater recharge in and between these contrasting aquifer systems. In the subsurface, this kind of juxtaposition forms a permeability contrast between relatively low, fracture-dominated permeability in crystalline rocks and relatively high permeability dominated by intergranular pore spaces variably filled by heterogeneous cementation in the basin-fill sediments that may allow relatively unimpeded mountain block recharge to occur.

Although there is not a continuous, large-displacement mountain-front fault that juxtaposes the Santa Fe Mountains against the Española Basin, clear variations of fault-zone internal structures controlled by host lithology and state of consolidation form important and heterogeneous impacts on groundwater flow within the bedrock-aquitard system. In Española rift-flank basement-rock aquifers, faults with fractured damage zones may be discrete conduits or conduit-barriers that may enhance local mountain block recharge to basin-fill aquifers. This may be particularly important if the orientation of such a fault zone is subparallel to the regional hydraulic gradient, as is the case for the Santa Fe fault oriented at a high angle to the mountain front (Fig. 7). In contrast, the poorly lithified basin sediments tend to produce faults with long, thin but semi-continuous, clay-rich cores and without open fractures in damage zones (Figs. 6, 9, and 11; e.g., Heynekamp et al., 1999; Minor and Hud-
son, 2006; Caine and Minor, 2009). Many of these faults are oriented nearly perpendicular to the regional hydraulic gradient, and in combination with their relatively low-permeability fault cores, form local barriers that impede basinward groundwater flow (e.g., Johnson et al., 2013).

Other geological heterogeneities that may influence the occurrence, recharge, storage, and flow of groundwater within the Santa Fe mountain block include a permeability contrast between crystalline bedrock aquifers and overlying sedimentary rocks bounded by a geologically complex but laterally extensive unconformity (e.g., Figs. 4 and 9). Proterozoic crystalline rocks tend to be pervasively jointed, showing networks of varying intensities, orientations, and spacings as well as numerous, hydraulically open single-fault fractures (Fig. 8; e.g., Caine and Tomusiak, 2003). In spite of these locally open structures, crystalline bedrock commonly constitutes low-bulk-permeability aquifers. However, overlying, locally higher-permeability sedimentary rocks can be important aquifers and should be considered in conceptual model development in mountain block–basin aquifer systems.

Laterally extensive, crystalline rock–sedimentary rock unconformities in and of themselves should also be considered as potentially important heterogeneities in general that could impact groundwater. As exemplified by the Española rift-flank Proterozoic-Paleozoic unconformity, there are locally thin marl units, massive limestone units (some with possible karst features), lenses of coarse sandstone, a variety of regolithic materials deposited on the crystalline rock paleo-erosion surface, variably weathered bedrock, and pervasive joint networks that cut the unconformity (e.g., Fig. 9). At local scales, these features, in conjunction with faults, may have a significant impact on recharge by allowing temporary storage and subsequent drainage into deeper crystalline rock aquifers.

Fault-bounded and other mountain block–basin configurations common in the western United States and elsewhere show a variety of combinations of geological heterogeneities very similar to those found in the eastern Española rift-flank-basin system that may have significant impacts on the recharge and flow of groundwater and solutes. The detailed approach to brittle structural characterization presented here, including identification of likely geologic heterogeneities and consideration of their relative hydraulic properties, informs conceptual models important in any comprehensive water resource assessment addressing geologic framework interactions with paleo– and present groundwater processes.

Regional Significance of Española Rift-Flank Fault Kinematics and Implications for Transpressional Deformation

The contractional and strike-slip fault kinematic data collected along the eastern rift flank of the Española Basin provide insight into local manifestations of the evolving Laramide strain and stress fields generally consistent with results proposed by others (Chapin and Cather, 1981; Erslav, 2001). Yet, it is unclear if and how the contractional kinematic results from the Española Basin flank relate to regional, predominantly dextral separation recorded along the NNE- to north-striking Picuris-Pecos fault ~20 km to the southeast (Fig. 2; Cather et al., 2008, 2011). The Picuris-Pecos fault reportedly has a protracted and complex deformational history spanning at least Ancestral Rocky Mountains, Laramide, and Rio Grande rift deformation events. It is intriguing to note that a few of the more prominent NE-striking, steeply dipping faults in the Española Proterozoic flank, such as the Santa Fe fault, show evidence for sinistral strike slip based on slickenline and shear-sense data (Fig. 7). The orientations of the faults and their kinematics are suggestive that they could have been “wrench” faults between the Picuris-Pecos and other northerly striking basement structures such as those associated with the Agua Fria fault system underlying the Española Basin sediments as delineated by Grauch et al. (2009) (Figs. 5 and 6).

In order to better understand the brittle progressive deformation represented by the reverse and strike-slip faults observed in the Española rift-flank basement rocks, better relative and/or absolute timing of fault slip are required. There is a growing body of evidence that kinematic (and paleostress) analyses without such timing information may have limited ability to resolve multi-event, deformational strain fields where there is heterogeneously faulted and fractured bedrock. The 1995 Kobe, Japan; 2002 Denali, Alaska; and 2008 Wenchuan, China earthquakes all showed initial reverse first motions directly followed by strike-slip motions, and for the Kobe and Wenchuan earthquakes, fault surface-rupture slip data show reverse and strike-slip slickenlines from the same event (cf. Spudich et al., 1998; Erslav, 2001; Eberhart-Phillips et al., 2003; Pan et al., 2014). Therefore, without timing information, distinguishing strain partitioning from progressive strain or other processes, such as dynamic rupture propagation, using fault slip data measured in ancient rock is difficult and potentially tenuous. For example, it cannot be ruled out that the reverse and strike-slip faults observed in the rocks flanking Española Basin formed from strain partitioning during single deformation events in contrast to temporally separated events associated with progressively rotating stress fields (cf. Erslav, 2001).

Challenges of Interpreting Fault Length Data and Derived Power Law Exponents

To the extent that a statistical fitting approach accurately reflects physical properties of the central Rio Grande rift data set, even at R² = 0.95, it is common that some of the longest and some of the shortest faults in the study area are not well represented by a power-law distribution. Additionally, there are a number of jogs in the fault rank curves that are “smoothed” by the power-law fit in log-log space (Fig. 13). While goodness-of-fit tests confirm that the power-law function is an appropriate fit to the majority of the data (Table 1), the values of the power-law exponent (C) may not be properly estimated (Bonnet et al., 2001; Newman, 2005; Clauset et al., 2008). The primary challenge in estimating C is determination of the cause(s) of the deviation of data from a power-law distribution at short and long fault lengths. If such tail regions of the data are predicted to reflect physical processes such as relative rate of fault growth or structural and stratigraphic boundaries, the exclusion of data in these regions...
may be appropriate (cf. Cladouhos and Marrett, 1996; Hardacre and Cowie, 2003). However, tail regions of the data may also result from undersampling of especially short and/or long faults (Marrett and Allmendinger, 1992), in which case the fitting approach may slightly over- or underestimate \( C \) depending on the lengths of faults undersampled.

In the central Rio Grande rift data set of magnetic fault lineaments, truncation or undersampling of short faults is likely mainly a function of the grid spacing (50 m) of the aeromagnetic data. Magnetic fault lineaments with lengths <100 m (spanning two grid points) cannot be resolved; lengths between 200 and 100 m (a span of 2–4 grid points) may be discounted due to lack of confidence in the interpretation. Censorship, or incomplete measurement of the longest faults that transect the study area boundary, was corrected by omitting faults whose tips intersected the aeromagnetic survey boundary (Fig. 5). Other biases inherent in the fitting of empirical data include problems of interference from neighboring anomalies and loss of resolution where fault throw is reduced, such as near fault tips, or where there may be insufficient rock magnetic contrast in the near surface to produce an anomaly, even if there is significant fault offset. Interference is a large problem in areas of complicated fault patterns, of high-intensity faulting, and near strongly magnetic volcanic or Proterozoic rocks that cause anomalies that mask those associated with faults.

Evaluation of the existence of characteristic length scales and associated values of \( C \) for central Rio Grande rift fault length data are challenging to relate to the variety of physical processes involved with the nucleation, growth, and evolution of the fault network. Particular physical effects relevant to the distribution of central Rio Grande rift fault length data and the degree to which they are characterized by a power-law distribution include: (1) likely groundwater saturation of somewhat homogenous, poorly lithified porous media leading to bulk weakness; (2) strain localization in clay-rich gouge fault cores that exhibit low-temperature, low-pressure ductile behavior dominated by particulate flow (e.g., Rawling and Goodwin, 2003, 2006; Caine and Minor, 2009); and (3) mixed shear and opening-mode deformation at fault tips and relays partly expressed as changes in slickenline orientations that tend to increasingly deviate from dip slip with curvature of the fault tip (Caine and Minor, 2009; Minor et al., 2013).

The value of \( C \) has been postulated to reflect fault growth by linkage at tip regions where shorter faults join to become longer faults, in contrast to discrete faults that continue growth from their tips without linking to other nearby faults (Cladouhos and Marrett, 1996; Xu et al., 2010). The median of 27 values of \( C \) reported in the literature is 1.37; however these data were derived from a large range of fault lengths, geological settings, and methods used for plotting data and estimating \( C \) (compilations from Cladouhos and Marrett, 1996; Bonnet et al., 2001; Xu et al., 2010). When fit to a power-law distribution at \( R^2 = 0.95 \) the computed values of \( C \) are 1.14, 1.16, and 1.22 for the Española, Santo Domingo, and Albuquerque Basins respectively, which are on the lower end of the reported spectrum. For power-law fits to 100% of the fault length data in each of the individual basins, the median is 1.29 with the lowest \( R^2 \) value being 0.84 (Table 1).

Xu et al. (2010) made the point that fault trace length measurements are made at a discrete stage in the evolution of a fault network and that it is likely that more than one range of length scales, for a given distribution of faults, has undergone linkage, which can lead to variability in values of \( C \) and thus uncertainty in the role of fault growth by linkage. Geometric evidence for fault linkage is not obvious in the aeromagnetic data (Fig. 5), but there is field evidence for some longer central Rio Grande rift intrabasin faults where growth by fault linkage has occurred (Caine and Minor, 2009). At a much smaller scale, within individual fault zones, Doughty (2003) and Caine and Minor (2009) interpreted that large-displacement, large-trace-length faults with single, discrete fault cores fundamentally grew by fault linkage in the direction of normal dip slip and along strike.

Because of limited exposure in the Española Basin and flank and the fact that many faults there are buried, there were very few places where fault displacement could be determined, so correlations between core width and displacement could not be evaluated. However, most of the faults in the flank rocks have relatively short trace lengths compared with those in basin-fill sediments. To the extent that fault length versus fault displacement scales as a power-law function (e.g., Shipton et al., 2006), it does appear that there is a higher degree of strain localization in the relatively weak basin sediments with narrow fault core widths compared with wider fault core widths observed in the crystalline and sedimentary rocks of the rift flank. Although there is poor knowledge of fault displacement, there is a disproportionately large number of faults with kilometer-scale lengths buried in each basin, suggesting that there may be greater total extensional strain along fewer faults than previously recognized.

**End-Member Deformational Processes Reflected in Fault Zone Mineralogy and Chemistry**

The amount of mineralogical and elemental chemical changes observed in the Española Basin faults likely reflect the degree to which end-member deformational processes are operative in controlling fault-related geochemistry in general. End-member processes include the physical entainment of material from a protolith into a fault core with little chemical reaction or chemical reactions focused in damage zones and in fault cores as they evolve. Elemental signatures also reflect differences in these end-member processes in combination with influence of protolithology. Major and trace elements appear progressively more changed as a partial function of protolith age and/or possibly burial depth. Faults dominantly in Proterozoic basement rocks show highly fractured damage zones with well-developed preferential argililization of plagioclase consistent with intermediate hydrothermal alteration (cf. Parry et al., 2002); faults dominantly in Paleozoic sedimentary rocks show poorly developed damage zones with limited evidence for the effects of hydrothermal alteration, and faults in poorly lithified Tertiary basin-fill sediments show few damage zone-related, open fractures and little to no evidence of fault-related hydrothermal fluid flow or alteration. Fault geochemistry in Tertiary basin-fill sediments therefore shows effects most akin to physical entainment processes where clay-rich fault cores are derived from protolith clay units with
only minor influences of geochemical reactions. This is reflected in the cores retaining relatively high trace element concentrations likely native to the protolith clay units from which they came, similar to that observed by Caine and Minor (2009) for the San Ysidro fault in the Albuquerque Basin. In comparison, Proterozoic and Paleozoic fault rocks show evidence for hydrothermal alteration, depletion of select trace elements, and near-isochemical mineral transformations in addition to entrainment.

**CONCLUSIONS**

Integration of multiple types of data and analyses from aeromagnetics, maps, outcrops, thin sections, mineralogy, and elemental chemistry for the central Rio Grande rift reveals a diverse array of structures formed in Earth’s brittle crust. The structures record many aspects of the tectonic evolution of the eastern flank of the central Rio Grande rift and adjacent Española Basin. Outcrop-based information also provides insight into the controls that geologic structures have in the occurrence, storage, and flow of surface and groundwater resources in the entire rift as well as the Rocky Mountains region as a whole. The data and approaches presented provide a holistic view of structural geologic features and processes and their effects on fluid flow widely applicable to other deformed regions of the Earth’s shallow crust. Several conclusions can be made from the results presented.

(1) Proterozoic crystalline rocks on the eastern flank of the Española Basin deformed in the brittle regime at least during the Laramide orogeny and during rifting. Contractual fault slip data from the basement are compatible with progressive, incremental strains identified in previous work (Chapin and Cather, 1981; Erslev, 2001) showing initial west-east shortening that rotated counterclockwise to north-south during the Laramide orogeny through a period transitional to early Rio Grande rifting. Extensional fault slip data in Proterozoic rocks are consistent with NW extension that may have reactivated preexisting (Laramide age?) contractual structures. Reactivated Proterozoic ductile structures or metamorphic fabrics were not observed.

(2) Extensional faults within Tertiary poorly lithified sediments of the Española Basin are more northerly striking than their counterparts in Proterozoic rocks. Slip data from these faults are consistent with typical WNW-ESE to west-east Rio Grande rift extension. Differences in the extension directions recorded among Proterozoic basement rocks and adjacent basin sediments may be related to the influence of strength contrasts and differences in anisotropy of preexisting basement faults compared with new faults that formed in the relatively weak, more isotropic sediments. This conceptual model is relevant to understanding tectonic interactions and evolution of rift basins underlain by mechanically contrasting well-indurated and crystalline rocks common globally.

(3) Many single, discrete fault cores were observed in crystalline basement rocks as well as in poorly lithified basin sediments. In crystalline rocks, fault cores are bounded by polished and striated slip surfaces with damage zones composed of relatively high-intensity, open fractures. In contrast, fault cores in basin sediments are bounded by unpolished to weakly polished, and some groove and trough, slip surfaces with weakly developed damage characterized by deformation bands. These observations highlight and further confirm conceptual differences in the internal structure of faults formed in rock being combined conduit-barriers with fractured damage zones versus faults in poorly lithified sediments that typically lack opening-mode fractures and thus may behave as partial barriers to groundwater flow.

(4) Aeromagnetic lineaments are a unique proxy for the length of buried faults in the Española and adjacent Santo Domingo and Albuquerque Basins. Fault length data derived from such lineaments confirm that there are many more and longer buried faults in the basins than known from surface mapping alone. Field observations, mapped fault geometries, and power-law fits to fault length data that have low exponent (C) values are all consistent with fault linkage as an important fault growth mechanism in poorly lithified basin fill of the central Rio Grande rift. Rift-basin C values also match values reported for a large variety of other rock types globally, further supporting fault growth by linkage as a fundamental process in upper crustal deformation.

(5) The mineralogy and chemistry of fault-related rocks and sediments show characteristic diversity. In Proterozoic granitic rocks, the primary fault-related geochemical changes reflect initial argillic hydrothermal alteration, subsequent weakening, and strain localization in fault cores characterized by nearly isochemical transformation of feldspars to clay minerals. In contrast, faults in basin-fill sediments are characterized by thin clay-rich fault cores developed primarily by mechanical entrainment of basin mudstone units and only minor secondary chemical and mineralogical changes. A high degree of strain localization in such clay cores may have facilitated fault growth and linkage as suggested by the fault length distributions.

(6) Large irregularly shaped and smaller dike-like breccia bodies are present throughout the Proterozoic basement rocks. These enigmatic breccias are distinct from fault breccias; they are not bounded by slip surfaces but have irregular intrusive contacts with surrounding host rocks; most are autoclastic and isochemical with respect to host rocks and have angular clasts that appear to have formed in a single event. In contrast, fault-related breccias show subdued, comminuted clasts with internal clast brecciation indicative of multiple deformation events. The enigmatic breccias are of limited spatial extent, both proximal and distal to outcrops of shatter cones believed to be related to a pre-Pennsylvanian bolide impact event. Weak iridium enrichment, relative to average continental upper crust, is associated with the breccias and adjacent protoliths. If the breccias are related to the shatter cones and an impact event, they may have been caused by the passage of the impact shock wave and may reflect hydraulic fracturing of the shal-
low crust in the vicinity of the shatter cones. However, without more spatially extensive iridium and other platinum group element and/or geochronologic data, an impact-related origin cannot be confirmed.

(7) The lithological contrast between exhumed crystalline basement rocks and the poorly lithified basin-fill sediments along the mountain front of the Santa Fe Mountains has been previously shown to be a critical interface for surface-water runoff and groundwater recharge. Geologic structures such as brittle faults, joints, and breccia bodies characterized in this study are the fundamental components of bulk porosity and permeability in the mountain-block crystalline rock aquifer system compared with the intergranular porosity and permeability of the basin aquifer system. Major fault zones within and along the mountain front are discontinuous along their traces and in their internal structure; there is little evidence that they act as regional barriers to mountain-block recharge into the basin aquifers. Breccia bodies are likely not large enough to constitute aquifers in and of themselves. No major, naturally occurring fault- or breccia-related geochemical anomalies were identified that could act as contamination sources for ground or surface waters. However, faults in the exhumed rift flank and adjacent rift basins are major geological heterogeneities that control local aquifer compartmentalization and host local geochemical anomalies in groundwater.

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REFERENCES CITED

Caine et al. | Survey of brittle structures, Rio Grande rift, New Mexico

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Connell, S.D., Koning, D.J., and Cather, S.M., 1999, Revisions to the stratigraphic nomenclature
Fankhauser, S.D., and Erslev, E., 2004, Unconformable and cross-cutting relationships indicate
Fackelman, S.P., Morrow, J.R., Koeberl, C., and McElvain, T.H., 2008, Shatter cone and micro-
Evans, J.P., 1990, Textures, deformation mechanisms, and the role of fluids in the cataclastic
crushed by the displacement of Proterozoic sediments, proposed by the displacement of late
Haley, J.J., and Jones, W.R., 1964, Chemical aspects of hydrothermal alteration with emphasis
Heynckem, M.R., Goodwin, L.B., Mosley, P.S., and Haneberg, W.C., 1999, Controls on fault-
zone architecture in poorly lithified sediments, Rio Grande rift, New Mexico: Implications for fault-zone permeability and fluid flow in, Haneberg, W.C., Mosley, W.A., Moore, J.C., and
Fackelman, S.P., Morrow, J.R., Koeberl, C., and McElvain, T.H., 2008, Shatter cone and micro-
scopich shock-alteration evidence for a post-Paleoproterozoic terrestrial impact structure
Fankhauser, S.D., and Ersliev, E., 2004, Unconformable and cross-cutting relationships indicate
major Precambrian faulting on the Picuris-Pecos fault system, southern Sangre de Cristo
Mountains, New Mexico, in Karlstrom, K.E., Humphreys, E.D., eds., Persistent influence of Proterozoic accretionary boundaries in the tectonic evolution of southwestern North America: Interaction of cratonic grain and
Jędrzej, M., 1997, Hydrothermal breccias in vein-type ore deposits: A review of mechanisms, mor-
Johnson, P.S., Koning, D.J., and Partey, F.K., 2013, Shallow groundwater geochemistry in the
Esperance Basin, Rio Grande rift, New Mexico: Evidence for structural control of a deep ther-
Grauch, V.J.S., and Hudson, M.R., 2007, Guides to understanding the aeromagnetic expression of
faults in sedimentary basins: Lessons learned from the central Rio Grande rift, New Mex-
Kelley, V.C., 1979, Tectonics, middle Rio Grande rift, New Mexico, in Riecker, R.E., ed., Rio Grande
Rift: Tectonics and Magmatism: American Geophysical Union Special Publication 14, p. 57–
70, doi:10.1029/SP014p0057.


