Structural contour maps of the base of the Santa Fe Group and two Neogene stratigraphic surfaces in the northern Española Basin, New Mexico

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EXECUTIVE SUMMARY

Structural contours of three stratigraphic surfaces in the northern Española Basin are presented in this report. These contours will be used by INTERA, Inc., to construct a geologic framework model for the Española Basin. The geologic framework model will, in turn, be incorporated into a groundwater model of the Española Basin being jointly developed by the U.S. Department of Interior (Bureau of Indian Affairs) and the New Mexico Office of the State Engineer. The study area spans most of the Abiquiu embayment (a faulted structural platform northwest of Española), the Española area, the Peñasco embayment (located northeast of Española), and a complex structural zone that includes the Santa Clara and Velarde grabens plus the southern Embudo fault system.

The three contoured stratigraphic surfaces are the: (1) top of the uppermost bedrock unit (which may be Oligocene volcanic flows, Mesozoic strata, Paleozoic strata, or Proterozoic crystalline rocks, depending on location); (2) base of the middle Santa Fe Group; and (3) base of an amalgamated package of Upper Miocene through Lower Pleistocene volcanic and volcaniclastic rocks belonging to the Jemez Mountains volcanic field. In the bedrock unit, Mesozoic strata are probably restricted to the extreme western and northwestern parts of the study area (see Baldridge et al., 1994). The middle Santa Fe Group includes the Ojo Caliente Sandstone Member of the Tesuque Formation, the Vallito and Hernandez Members of the Chamita Formation, and the Cuarteles and Cejita Members of the Tesuque-Chamita Formations (note that the Cuarteles and Cejita Members extend from the Chamita Formation eastwards across the Rio Grande into the Tesuque Formation). Upper Miocene through Lower Pleistocene volcanic rocks of the Jemez Mountains volcanic field contain the Canovas Canyon Rhyolite, the lower and upper Bandelier Tuffs (i.e., Tshirege and Otowi Members), and the Paliza Canyon, Lobato, Tschicoma, and Puye Formations. Mafic volcanic rocks are only contoured where more than ~600 ft thick. Structural contours (1000 ft contour interval) representing the dipping planes of major fault lines are also drawn. These faults include the El Rito, East Lobato Mesa, Cañada del Amalgre, North Pajarito, West Medanales, Middle Medanales, East Medanales (new names for all three Medanales fault strands), Ojo Caliente, West Black Mesa (new name), East Black Mesa (revised name), West Vibora (new name), East Vibora (new name), Santa Clara, Gaucho, Guique (new name), La Mesita, Velarde, Rio de Truchas, and Peñasco faults.

The two main datasets used for the contouring effort were: (1) mapped contacts and attitude data from existing geologic maps; and (2) a model of the top of bedrock obtained by gravity inversion techniques (Grauch et al., 2009). Other important input data include Bouguer anomaly gravity data, depth interpretations of seismic reflection lines published in Ferguson et al. (1995), cross-sections from existing geologic mapping, and drill-hole data.

The resulting structural contour maps are, in effect, the author's preferred model of the subsurface that is allowed by (consistent with) the available datasets. Comparison of the gravity inversion-based model of bedrock elevation with independent analyses by Harper (2015) across the study area yields an estimate of vertical error of the top-of-bedrock contours that is typically 10–30%. Using a ±2° error in projection of the base-of-middle-Santa-Fe-Group contact and adding a 20% safety margin results in typical maximum vertical errors of 30-50%, with the higher end of that range likely being in the Velarde and Santa Clara grabens. Even greater vertical errors (mostly >30%) are likely in the Jemez Mountains west of the southward projection of the East Lobato Mesa fault and the Pajarito fault zone. In some places there is at least one reasonable alternative in the structural contouring. One such locality lies between the Chamita syncline (located 5–6 miles north of Española) and the mouth of Rio de Truchas. Here, the La Mesita fault was extended southwards towards the Santa Clara fault for the artificial purpose of making the Embudo fault system a continuous groundwater barrier for the aforementioned groundwater model. In actuality, the La Mesita fault could very well project more eastward (to the Guique fault), resulting in a larger right-step (1.5 mi) between the Guique fault and the north end of the Santa Clara fault.

Several discoveries were made by the structural contouring. First, the gravity gradient near the west margin of Black Mesa is ascribed to a newly delineated fault under the eastern margin of the lower Rio Ojo Caliente valley. Second, the Abiquiu embayment has 1000–2000 ft of structural relief due to faults offsetting the corresponding structural platform. Third, there is a 30–40° discrepancy in strikes between the top of bedrock and the base of the middle Santa Fe Group northeast and southwest of Española, which could be due to deposition of early Santa Fe Group over paleotopographic relief on a former Laramide-age highland.

Comparison of the relative vertical offsets (throw) by major faults of the top-of-bedrock vs. base-of-middle Santa-Fe-Group contours allows preliminary inferences about the age range of fault activity. Higher confidence interpretations await site-specific analyses of errors. Santa Fe Group deposition started about 26 Ma, and the age of the base of middle Santa Fe Group is 13–13.5 Ma (Koning et al, 2013), about midway between initiation of extension and present-day. Where throw values are similar for the two contour sets, then primary activity on those structures hypothetically occurred after 13-13.5 Ma. Preliminary evidence suggests that such late-rift structures may include the Cañada del Amalgre, southernmost Ojo Caliente, and Velarde faults. The southernmost Ojo Caliente fault appears to have generated a north-south, east-tilted half-graben; the base-of-middle-Santa-Fe-Group and top-of-bedrock surfaces in this graben dip eastwards at comparable magnitudes, consistent with a seismic reflection line (Rio del Oso, Ferguson et al., 1995). Where the top-of-bedrock surface has about twice the throw as the base of middle Santa Fe Group, then relatively continuous activity is inferred, at least for a few million years before and after 13–13.5 Ma. Such structures may include the East Black Mesa fault, Rio de Truchas fault, and Santa Clara fault. Where the throw of the top-of-bedrock surface is much more than the throw of the middle Santa Fe Group base, then such structures may have been primarily (but not exclusively) active prior to 13–13.5 Ma. Such pre-13.5 Ma structures include the West Black Mesa fault and possibly the Ojo Caliente fault north of where it crosses the Rio Ojo Caliente.

These preliminary fault activity constraints are consistent with previous interpretations (Koning et al., 2004a, 2016) regarding evolution of strain transfer across the left-stepping southern San Luis Basin and the northern Española Basin. Prior to 10–13 Ma, the Velarde graben acted as a pull-apart graben in a west-east to WNW-ESE regional stress field, very likely tilted westward towards the West Black Mesa fault, and was structurally isolated from the Santa Clara graben to the south. Eventually, evolution and growth of the Embudo fault system created a continuous fault system, probably ca. 10–12 Ma, between the southern San Luis Basin and northeastern Española Basin. Subsequently, left-oblique strain was focused on the Velarde, La Mesita, Guique, and Santa Clara faults, and the primarily normal-slip West Black Mesa and Ojo Caliente faults experienced a dramatic decrease in throw rates.

INTRODUCTION

Purpose

In order to better characterize subsurface stratigraphy and structure in the northern Española Basin, structural contours were drawn for three stratigraphic surfaces. The three stratigraphic surfaces are: (1) the top of the uppermost bedrock unit—which may be Oligocene volcanic rocks, Mesozoic strata, Paleozoic strata, or Proterozoic crystalline rocks, depending on location; (2) the base of the middle Santa Fe Group (Chamita Formation and the Cejita, Cuarteles, and Ojo Caliente Sandstone Members of the Tesuque Formation); and (3) the base of an amalgamated package of Upper Miocene through Lower Pleistocene volcanic and volcaniclastic rocks belonging to the Jemez Mountains volcanic field.

The project was funded by Ohkay Owingeh Pueblo. The immediate purpose of the project was to construct a geologic framework model being developed by Intera, Inc., for the Española Basin. The geologic framework model will, in turn, be incorporated into a groundwater model of the Española Basin being jointly developed by the Bureau of Indian Affairs (U.S. Department of the Interior) and the New Mexico Office of the State Engineer. Additionally, these structural contours should prove useful for future and current geologic endeavors that have a component of stratigraphy or structure in the Española Basin.

Study Area

Several boundaries related to the aforementioned geologic framework model are shown in Figure 1; note that this figure does not show the southern part of the model area. The outer boundary (heavy purple line) is the final boundary of the geologic model, with the internal boundary (orange line) dividing previous efforts (to south) from new efforts (to the north). Pre-existing efforts correspond largely with the geologic model of Cole et al. (2009). However, to edge-match the new effort with the pre-existing geologic model, the Cole et al. (2009) contours in the yellow-shaded region of Figure 1 required modification.

The general “study area” is the region within the pink line in Figure 1, which includes the yellow-shaded area of contour adjustment from Cole et al., 2009. This pink line corresponds to the extent of the top-of-bedrock contours. Note than an elongated area of adjustment of the Cole et al. (2009) contours for the base of the middle Santa Fe Group extends southwards along the Rio Grande that is not shown in Figure 1 (but is depicted in Plate 2). Figure 2 illustrates the major faults in the study area and locations of relative deep sub-basins within the larger Española basin. The study area includes the Española area, most of the Abiquiu embayment to the northwest, all of the Peñasco embayment to the northeast, and the structurally complicated Embudo fault system in between (Figs 1–2).

The structural deepest parts of the study area, the Santa Clara and Velarde grabens (Ferguson et al., 1995; Koning et al., 2004a), lie in the middle of the study area (Fig. 2). These grabens are flanked on the northwest by the Abiquiu structural platform (underlying the Abiquiu embayment) and to the east by a hanging wall ramp that dips westwards towards the Santa Clara and Velarde grabens. Collectively, these two deep, “inner” grabens and the hanging wall ramp are called the Eastern Española basin half-graben by Koning et al. (2013).

Numerous faults cut the Abiquiu structural platform and the hanging wall ramp southeast of Española (Fig. 2). Fewer faults are present in the hanging wall ramp northeast of Española. The Santa Clara graben is bounded on the west by the Santa Clara and North Pajarito faults. The Santa Clara fault extends northward to the Chamita syncline (Fig. 2). The Velarde graben is bounded by the West Black Mesa fault (new name) to the west and the Velarde fault to the east. The northeast-striking, left-oblique, La Mesita fault extends into the middle of the Velarde graben from the north.

Stratigraphy

The stratigraphy of the study area is illustrated in Figure 3. In this figure, formation-rank contacts are shown by heavy black lines. Upper Miocene-Lower Pleistocene volcanic rocks (reddish shade on Fig. 3) include the Paliza Canyon Formation and Canovas Canyon Rhyolite, the Tschicoma and Puye formations, and the Tshirege and Otowi members of the Bandelier Tuff.

Note that the Puye Formation is included in the volcanic unit, even though it is primarily composed of volcaniclastic sedimentary rocks. The age of the base of the Keres Group, which includes all the volcanic units listed above except for the Bandelier Tuff (Kelley et al., 2013), is placed at ~13 Ma based on coarse, locally derived, dacitic tephra beds of that age in the lowest parts of the Chamita Formation that are inferred to be derived from the Jemez Mountains volcanic field; Koning et al., 2007a).

The Keres Group interfingers with the Chamita Formation west of the Rio Grande (Fig. 3). The Chamita Formation includes the Hernandes, Vallito, Cejita, and Cuarteles members (Koning and Aby, 2005). The Cejita and Cuarteles members extend eastward across the Rio Grande into the Tesuque Formation. These units, in addition to the Ojo Caliente Sandstone Member of the Tesuque Formation (an eolianite), are included in the middle Santa Fe Group. The middle Santa Fe Group is overall coarser-grained than lower Santa Fe Group strata (Koning et al., 2005c, 2013), and is thus inferred to have relatively higher permeability. This inferred change in permeability is the reason that the middle Santa Fe Group was differentiated from the lower Santa Fe Group. However, there may be areas in the study area, particularly over the deeper parts of the Velarde and Santa Clara grabens, where the middle Santa Fe Goup may be relatively fine-grained due to syn-depositional subsidence. The upper Santa Fe Group is largely not preserved in the study area, with the exception of the Puye Formation (which was combined with the volcanic unit).

The lower Santa Fe Group includes the Tesuque and Abiquiu formations (Fig. 3). Tongues of relatively thin basaltic rocks may be present in the lowermost Santa Fe Group. Below the lower Santa Fe Group, an angular unconformity is likely present across much of the basin, separating basin fill (above) from bedrock (below). Bedrock includes Oligocene volcanic rocks, Paleozoic-Mesozoic sedimentary rocks, and Proterozoic crystalline bedrock (granite, gneiss, schist, and amphibolite). Mesozoic sedimentary rocks are likely restricted to the westernmost part of the study area (Baldridge et al., 1994).

Units of Measurement

In consideration of the geologic model of Intera, Inc., this report uses English units of measurement. The structural contours are given in feet (elevation above sea level). In the text below, we present distances in miles. To convert from feet to meters, divide by 3.281. To convert from miles to kilometers, multiply by 1.609.

DATA SOURCES

Structural contours of the three stratigraphic surfaces were drawn using the following data sets. The highest-confidence dataset were geologic maps, drill holes, and seismic reflection data. Geologic maps (1:24,000 scale) of the area of interest depict contacts where the three stratigraphic surfaces intersect the Earth's surface, thus providing local horizontal and vertical constraints for structural contouring. The maps also show attitude data, which allow subsurface extrapolation from these mapped contacts. The geologic maps include: Guaje Mountain (Kempter et al., 1998), Española (Koning, 2002), Cundiyo (Koning et al., 2002), Vallecitos (Kempter et al. (2005), Chili (Koning et al., 2005a), San Juan Pueblo (Koning and Manley, 2003), Chimayo (Koning, 2003), Truchas (Smith et al., 2004), El Valle (Aby and Timmons, 2005), Medanales (Koning et al., 2004b), Lyden (Koning, 2004), Velarde (Koning and Aby, 2003), Trampas (Bauer et al., 2005a), Peñasco (Bauer et al., 2005b), El Rito (Koning et al., 2008), Ojo Caliente (Koning et al., 2005b), and Taos Junction (Koning et al., 2007b). The only deep drill hole penetrating bedrock is the Castle Wigzell Kelly Federal Well; depth picks in this well are shown in Koning et al. (2002). Shallower drill holes that contained critical data for the base of the middle Santa Fe Group include the Agua Sana South #1 well, the Alcalde exploratory boring, the City of Espanola No. 3 well, and the Ohkay Owingeh Casino well (Fig. 2). Seismic reflection data (Ferguson et al., 1995) are from lines shot along the lower Rio Truchas (NW-SE), northern Black Mesa (N-S), lower Cañada Ancha (NW-SE), and Rio del Oso (NE-SW) (Fig. 2). In the seismic reflection lines, depths were estimated from the time data given in Ferguson et al. (1995) using the two-way travel-time velocities listed in Table 1.

Table 1. Santa Fe Group seismic velocities used to estimate depths along the Rio de Truchas, Black Mesa, Rio delo Oso, and Cañada Ancha seismic lines.

Time Range (two-way, in milliseconds)	Velocity (ft/sec)
0–800	7600*
800–1700	9500**

* From Biehler et al. (1991). **From Biehler et al. (1991) calibrated by the depth to the base of the Santa Fe Group in the Yates No. 2 well (depth given in Myer and Smith, 2006).

Two input datasets are based on modeling the top of bedrock (base of basin fill) using gravity techniques. A heavily used dataset was a contour map of the top of bedrock derived from a 3D gravity model constrained by drill holes and seismic reflection data—herein referred to as the "3D gravity bedrock-elevation model." Rated as moderate-confidence, this particular dataset is from Grauch et al. (2009). How it was constructed and a discussion of its limitations are presented in pages 24–27 of USGS Professional Paper 1761 (Grauch et al., 2009). A second, lesser used gravity-based model was a two-dimensional cross section constructed along the aforementioned seismic lines but extending west to Abiquiu (the NEBST cross-section of Harper, 2015). This cross section was created by projecting elevations and gravity data onto a 2-D profile line, and then using Geomod (a MATLAB script written by John Fersuon and Emily Hinz) to constrain a forward density structure model along the profile (Harper, 2015). The resulting 2-D profile is also rated as moderate-confidence.

Data sets rated as low-moderate confidence were cross-sections of the aforementioned geologic maps that lack subsurface constraints. These generally include all the maps, with the exception of five maps that have deep drill data or seismic reflection lines: Cundiyo, Lyden, Velarde, San Juan Pueblo, and Chili quadrangles.

METHODS

The structural contours were drawn directly into an ArcGIS database using ArcMap 10.4. The procedure for drawing structural contours for all three surfaces proved iterative. Guiding rules for the contouring were (listed in order of importance): (1) Contours must be offset along major faults that are listed above (shown as black lines on Figure 2); (2) Dips of strata must be approximately similar, or slightly more, than averaged dips shown on geologic maps; (3)

Stratigraphic displacements and throw values of exposed strata by faults, as determined by geologic mapping, should be of similar magnitude or less than stratigraphic displacements and throw for subsurface structural contours; (4) Stratigraphic displacements and throw by faults of older units should not be less than younger stratigraphic units (within the margin of error); (5) Top-of-bedrock dips should not be less than the dips of younger strata; (6) Contours must edge-match those drawn by Daniel Koning in the Cole et al. (2009) model of the southern Española Basin; (7) Contours must be approximately parallel to the general stratal strike direction shown on geologic maps; (8) Top-of-bedrock strikes should approximately parallel the contours from the 3D gravity bedrock-elevation model; and (9) Strikes of the base of middle Santa Fe Group should approximately mimic the strikes of the top of bedrock. There are local exceptions for #8 and #9, as elaborated in the Results and Discussion sections.

The top of bedrock was drawn first, followed by the base of the middle Santa Fe Group and Upper Miocene-Lower Pleistocene volcanic rocks of the Jemez Mountains volcanic field. For the top of the bedrock, structural contours were drawn away from outcrop control near Chimayo using strike and dip data from geologic maps. Extending the contours in this manner resulted in a mismatch with subsurface data in the Rio de Truchas seismic lines (Ferguson et al., 1995) and, to a lesser extent, the Kelly Federal Well. This observation led to iterative adjustment of the structural contours in the area east and northeast of Española, which resulted in a better match with the strike of the 3D gravity model contours. Contours for the top of bedrock were then drawn near Peñasco using the 3D gravity bedrock-elevation model, attitudes from geologic maps, and geologic map cross sections. Afterwards, contours for the top of bedrock were drawn south of Medanales using the Rio del Oso seismic reflection line, geologic map data, the 3D gravity bedrock-elevation model, and the cross-section of Baldridge et al. (1994). Geologic map data near Ojo Caliente allowed relatively confident subsurface projection of the top-of-bedrock contact in that area. From there, the contouring was extended between Ojo Caliente and the Rio Chama. The last place that top of bedrock structural contours were drawn was in the vicinity of the Embudo fault system; the contours were interpolated into this fault system from the east and the west.

The base of the middle Santa Fe Group has a smaller extent than the top of bedrock. The initial contours were drawn northwards, using geologic map attitude data, from outcrop control in the bluffs east of Española and north of the Santa Cruz River. Then, the base of the middle Santa Fe Group was drawn south of the Rio Chama using geologic map attitudes and fault displacement values calculated from map relations. From there, the contours were drawn to the north-northeast and to the south. Finally, these were interpolated into the Embudo fault system from the west and east; this interpolation honored fault throws determined from geologic map observations and geophysical data (Ferguson et al., 1995) as well as the top-of-bedrock contours. Discrepancies occurred between the strikes and dips of top-of-bedrock contours and base-of-middle-Santa-Fe-Group contours in the Chamita syncline north of San Juan Pueblo as well as near Cerro Roman (Figs. 1-2). There, both the top-of-bedrock contours and base-of-Santa Fe Group contours needed to undergo several iterative adjustments in order to conform to the nine guiding rules listed above.

Drawing the base-of-volcanic relied solely on the 1:24,000 geologic maps and previous contouring by Cole et al. (2009). The maps nicely showed where the surface daylighted north of Santa Clara Creek. South of Santa Clara Creek, there is high uncertainty (>30% vertical accuracy) about the subsurface geometry and depths of the base of this unit.

ESTIMATION OF VERTICAL ERROR

Vertical errors are an important consideration to any interpretations derived from the structural contours. Estimation of vertical errors are illustrated by shading on Plates 1-3. Areas of higher inferred accuracy (mostly <30% vertical error) are shown in yellow, those with lower accuracy (15-50% for the base of the middle Santa Fe Group) shown in peach-color, and those having very low accuracy (probably more than 30%) shown by pink-purple. The latter mostly lies under the Jemez Mountains.

Vertical errors of the top-of-bedrock contours are estimated to typically be 10–30% over the study area, with higher errors associated with the deeper parts of basins. A 15% vertical error value was obtained over central Black Mesa by comparing two independent interpretations of the top of bedrock: basin fill depths calculated from Harper (2015) and those estimated by the 3D gravity bedrock-elevation model (Grauch et al., 2009). This error was doubled to obtain a conservative maximum error value of 30%. In the area near the Valles caldera, there are greater vertical errors for the top of the bedrock (probably more than 30%) due to the paucity of gravity data and the breakdown of assumptions underlying the construction of the 3D gravity model (Grauch et al., 2009).

The maximum error of estimating depths and thicknesses of the middle Santa Fe Group and the base of the volcanic package is likely 30-50%. Contouring the middle Santa Fe Group base was typically done by averaging stratal attitude data in the geologic maps and using these data to project surface contacts into the subsurface. The estimated error in the stratal attitude dip data is ±2°. Typical dip values are 5–8°. The difference in the thickness in projecting a contact using the median dip value of 6.5° vs. 4.5° or 8.5° is 30%; another 20% is added to obtain a conservative maximum value of 50%. The same reasoning can be used to infer a maximum 30-50% vertical error for the base of Upper Miocene through Lower Pleistocene volcanic rocks.

A recently drilled borehole located 0.7 miles ENE of Ohkay Owingeh allows a test of the vertical error estimates and also provides an example of how vertical error is calculated. The ground surface at that location is 5740 ft asl and the model predicted that the base of the middle Santa Fe Group is 4570 ft, a depth of 1170 ft. In reality, the base of the Ojo Caliente Sandstone was found to be 750 ft depth. The calculated error is the difference in depth divided by the model depth, or (1170-750) / 1170 = 0.36. The 36% error is consistent with the lower accuracy polygon plotted there (peach shade on Plate 2, depicting an estimated vertical error of mostly 15-50%).

For the middle Santa Fe Group, errors are greatest where larger projection differences are involved because dip changes may not be recognized. Such areas would be the deeper parts of the Santa Clara and Velarde grabens. Other areas of relatively high error include east of Ojo Caliente, within 3 miles east of the southern El Rito fault, within 3 miles east of the northern El Rito fault, and within 2 miles west of the central Ojo Caliente fault. Another complication of projecting long distances is that lateral facies changes can occur, so that this relatively coarser-grained unit (compared to underlying strata) may be finer-grained in the aforementioned sub-basins. This lateral fining likely occurs in the Velarde graben based on limited well data, as illustrated by the northern part of the A-A’ cross section in plate 1 of Koning et al., 2013).

RESULTS

Plates 1 through 3 respectively show the resulting structural contours for the top of bedrock, base of middle Santa Fe Group, and base of Upper Miocene-Lower Pleistocene volcanics. Below, the results of the contouring effort are treated separately per geographic area. For comparison, Plate 4 depicts structural contours for both the top of bedrock and the base of the middle Santa Fe Group.

Abiquiu structural platform

The Abiquiu structural platform (*sensu* Baldridge et al., 1994) extends west from the west-dipping, west-down Ojo Caliente fault and west from the Santa Clara fault (Fig. 2). The configuration of the bedrock surface from the 3D gravity bedrock-elevation model agree reasonably well with mapped stratal attitudes. Although describing this area as a structural platform is appropriate in a broad sense, the platform is broken by numerous normal faults mapped in Koning (2004), Koning et al., (2004b), Koning et al. (2005a,b), and Kempter et al. (2005) (Fig. 2). Based on the contouring effort, the structural relief, mainly due to faulting, is about 1000–2000 ft (Plate 1). The top of bedrock varies from about 1000 ft elevation above sea level (asl) to 3,000 ft asl. The elevation of the top of basement rises to the south and also northwards near the northern study area boundary. The elevation of the base of the middle Santa Fe Group varies from about 5000 to 6100 ft asl (Plate 2). On the immediate footwall of the Santa Clara fault near Carro Roman, the base of the middle of the Santa Fe Group is modeled as being relatively high at 6,000-6,3000 ft asl (Plate 2).

Lateral displacement gradients along the longer faults have created sub-basins on their immediate hanging walls. The deepest sub-basins are between the Ojo Caliente and East Medanales fault (800–1000 ft asl of the top of bedrock; 5000–5600 ft thickness of Santa Fe Group), on the hanging wall of the Middle Medanales fault (1200 ft asl of top of bedrock; 4800–5200 ft thick Santa Fe Group), between the northern El Rito and West Medanales fault (1200 ft asl of the top of bedrock; 4800 ft thick Santa Fe Group), and immediately east of the southern El

Rito fault (1800 ft asl of the top of bedrock; 4000–4300 ft thick Santa Fe Group). A structural high near the Rio Chama appears to trend parallel to this river, where the elevation of the top of bedrock is ~2400 ft asl and the Santa Fe Group is ~3400–3500 ft thick.

Using stratal strikes and the 3D gravity bedrock-elevation model, the top of bedrock and the base of the middle Santa Fe Group dip SSW west of the intersection of the Ojo Caliente fault zone and Cañada Ancha (on the hanging wall of the Ojo Caliente fault), forming a ramp-like structure with 2200 ft of relief. The top of bedrock is inferred to be as deep as 800–1000 ft asl immediately south of this ramp and the base of middle Santa Fe Group as deep as 5000–5100 ft asl. Both surfaces gradually become shallower southward of this structural low on the hanging wall of the Ojo Caliente fault.

Considerable uncertainty exists in the Cerro Roman area due to the paucity of stratal and gravity data, but confidence in the structural contours increases northwards towards the Rio de Oso, an area that has a seismic reflection line (Ferguson et al., 1995) and abundant stratal attitude data. Steep southward dips of the Chamita Formation measured on the southern slopes of Cerro Roman (Koning et al., 2005a) require an east- to northeast-trending structural high on the south end of this topographic high. A structural ridge is inferred to extend northward from the eastern end of Cerro Roman and small structural depression drawn 1 mile north of Cerro Roman, but the lack of stratal and gravity data make these interpretations highly uncertain.

Several noteworthy structural features occur near Rio del Oso. At a distance of 2.5 miles upstream from the mouth of Rio del Oso, an unnamed, SW-down fault striking north to northwest has created a small graben on its immediate hanging wall. This structural low continues to the west towards the Cañada del Amalgre fault. The immediate footwall of the Cañada del Amalgre fault (west side) typically lacks preservation of the Middle Santa Fe Group. To the south-southeast of the mouth of Rio del Oso, stratal attitudes and the Rio del Oso seismic line indicates that the top-of-bedrock and base-of-middle-Santa-Fe Group stratigraphic surfaces dip steeply northeastwards towards the southernmost end of the Ojo Caliente fault, resulting in a pronounced structural low where the top of bedrock has an elevation of ~600 ft asl and the base of middle Santa Fe Group has an elevation of ~3800 ft asl.

North of Velarde graben

The 3D gravity bedrock-elevation model indicates a syncline that plunges southward and merges into the central, deeper part of the Velarde graben. This syncline can be considered as the northern end of the Velarde graben. The detailed geometry of this structure is uncertain due to the paucity of gravity data and geologic map attitude data in the area, but nonetheless the contours of both the top of bedrock and base of the middle Santa Fe Group were drawn to mimic the 3D gravity model. This interpretation results in minimal throw (~100 ft) on the northern East Black Mesa fault, which can be confidently mapped into this area from where it offsets the basalt cap of Black Mesa. The axis of the south-plunging syncline is interpreted to bend northwestward at a location 2.5 mi east of Ojo Caliente.

Calculated fault offsets and attitude data from Koning et al. (2007b) were used to model a south-plunging horst block 4 mi northeast of Ojo Caliente, bounded on either side by the West and East Vibora faults. Based on map relations, the East Vibora fault has about 100 ft of east-down throw and the West Vibora fault has 200 ft of west-down throw of the base of the middle Santa Fe Group. The top of the bedrock is inferred to have more vertical offset: 100–200 ft of east-down throw on the East Vibora fault and ~800 ft of west-down throw on the West Vibora fault. Contours in the area east of the horst block have relatively low vertical errors because of the availability of water well records (cross-section A-A' of Koning et al., 2007b).

Compared to the syncline, the confidence in the contouring is higher for the Ojo Caliente area and within 2 mi east of Ojo Caliente. This is due to good badland exposure resulting in tightly constrained mapped contacts for the base of the middle Santa Fe Group and the top of bedrock. There are also abundant, relatively consistent stratal attitudes (Koning et al., 2005b). The attitude data indicate a strike of ~010° near Ojo Caliente that bend to a strike of ~045° south of Ojo Caliente. Dips of the base of the middle Santa Fe Group are 5–8° E, but honoring the 3D gravity bedrock-elevation model necessitated steepening the top-of-bedrock contours to ~10–16° E.

Southward, to the narrow and wedge-shaped area between the Ojo Caliente and West Black Mesa faults, the top-of-bedrock contours are drawn with dips equal to or steeper than the base-of-middle-Santa-Fe-Group contours (by a factor of 1 to 2). The abundance of stratal attitudes gives relatively high confidence for the base-of-middle-Santa-Fe-Group contours. The magnitude of the dip of the top of the bedrock is uncertain in this area. A seismic reflection line in the lower reaches of Cañada Ancha (Fig. 2; fig. 9 of Koning et al., 2013) suggests relatively flat subsurface strata for both the top of the bedrock and overlying lower Santa Fe Group strata; however, tilted strata with ~5° SE dips are exposed alongside lower Cañada Ancha (note that the trend of the seismic line is southeast, parallel to the true dip direction). Similarly, the 3D gravity bedrock-elevation model indicates a southeast dip. Consequently, the 3D gravity model was utilized instead of the Cañada Ancha seismic line for drawing contours in this area.

East of Embudo fault system and the Peñasco embayment

Northeast of Española lies a region of minimal faulting and a broad, west-plunging syncline. In the west of this area, only two faults were contoured: the Velarde fault and the Rio de Truchas fault. These faults are discussed in the next section. The west-plunging syncline continues into this area from the Peñasco embayment (discussed below). Due to its thinness and presence above the saturated zone, the middle Santa Fe Group is not contoured more than 6 mi east of the Velarde fault.

Comparison of surface-based attitudes (from geologic mapping) with those obtained from the 3D gravity bedrock-elevation model indicate a notable disparity in strike and dips. Surface-based strikes are consistently 045 to 070°, whereas the gravity inversion-based bedrock elevation model indicates strikes of 010 to 030°. Confidence in strike discrepancy is relatively high because of the constraints provided by the Rio de Truchas seismic reflection line (Ferguson et al., 1995; Table 1). The area of discrepancy continues eastward until about the longitude of Chimayo. In an eastward direction, dip magnitudes of both surfaces are about the same until near the easternmost extent of the middle Santa Fe Group, where the top of the bedrock appears to be somewhat shallower than the base of the middle Santa Fe Group. An interpretation explaining these observations is given in the Discussion section below.

The Peñasco embayment spans the area occupied primarily by Santa Fe Group between the Picuris Mountains and Sangre de Cristo Mountains. Coincidently, the embayment lies east of the contouring of the base of the middle Santa Fe Group. Only the top of the bedrock is contoured in the Peñasco embayment, using available mapped stratal attitudes, elevation control where Santa Fe Group overlies bedrock on the surface, and the 3D gravity bedrock-elevation model.

Two structural features are evident. On the west is the aforementioned west-plunging, synclinal structure. A north-northwest trending bedrock high near El Valle separates this syncline from a structural low to the east, herein named the Peñasco structural basin. The Peñasco basin is inferred to have as much as 2600 ft of Santa Fe Group (including the Picuris Formation), which thickens northward from where Santa Fe Group onlaps basement rocks to the south. A northward-increasing throw gradient on the Peñasco fault (new name, Fig. 2) likely accounts for the northward thickening (deepening) trend. Within 3 mi south of the southern foothills of the Picuris Mountains, the top of the bedrock dips to the south. The northern part of this basin, therefore, approximates a syncline with an axis trending east-west.

East-central Española Basin

About 1-1.4 mi north of the Santa Cruz River, the top-of-bedrock structural contours bend from north-striking (to the south) to northeast-striking (to the north). This is consistent with a slight bend in the contours of the 3D gravity bedrock-elevation model. The bend is more obvious in Santa Fe Group stratal attitude data in Koning (2003). This flexure creates a northwest-plunging anticline projecting to Ohkay Owingeh. Between the Santa Cruz and Nambe Rivers, stratal strikes in Koning et al. (2002) are north to slightly east of north and dip about 5–8° west. However, a slightly northwest strike (350°) of the top-of-bedrock contours had to be drawn in order to edge-match with the contouring of Cole et al. (2010).

The dip of the top of the bedrock changes westward from the mountain front. Within 0.6 mi west of bedrock exposures in the Sangre de Cristo Mountain foothills (e.g., near Santa Cruz Lake), consideration of geologic map data yields westward dips of 20–25°W. This zone of steep dips corresponds to the north-striking Gabeldon structure of Koning et al. (2013). A 5–6 mi wide area of shallower modeled dips lies to the west of the Gabeldon structure, decreasing progressively from 8°W to 6°W (Plate 1). The eastern part of this area has relatively dense network of mapped normal faults; many of the larger faults have east-down throw (Koning et al., 2002). These faults were not explicitly incorporated into the contouring, so the result is a smoothing effect and an overall modeled dip that is less than the commonly measured 10–13°W dips on the surface (Koning et al., 2002). The dip of the top-of-bedrock contours increases to 12–14°W at the faulted Barrancos monocline (Koning, 2002; Koning et al., 2013). Mapped stratal attitudes in the Santa Fe Group (14–22°W) are steeper than the contoured top of the bedrock; again, this likely reflects the smoothing effect over a plethora of east-down normal faults that were not explicitly incorporated into the structural contours. Note that the prominent northwestward strikes northwest of Pojoaque follow the 3D gravity bedrock-elevation model rather than mapped stratal attitudes; the odd inflection here is probably due to gravity model limitations or basement heterogeneity, but nonetheless this northwest strike was necessary in order to edge-match with the top-of-bedrock contouring of the Cole et al. (2009) geologic model. Near the modern Rio Grande, the westward dip of the top of the bedrock is inferred to shallow to 6–7°W, consistent with exposures showing low-magnitude stratal dips west of the river. On the west side of the modern river valley, the base of the middle Santa Fe Group is interpreted to project eastwards (up-dip) to the base of late Quaternary alluvium.

Embudo fault system

The northern Embudo fault system in the study area includes the following faults whose fault planes were incorporated in the structural contours (listed from west to east): West Black Mesa, East Black Mesa, La Mesita, Velarde, and Rio de Truchas fault. One could reasonably argue that the Rio de Truchas fault is not part of the Embudo fault system. Between the West Black Mesa fault and the Velarde fault lies the Velarde graben. The Velarde graben was recognized and named by Manley (1976, 1979) for a north-south, structurally low area spanning the center of the Española Basin. However, Ferguson et al. (1995) interpreted three distinct structural lows using gravity data, which were named the Velarde, Santa Clara, and Pajarito grabens by Koning et al. (2004a). The revised Velarde graben extends northeast-southwest between the Rio Chama and the Embudo area (Ferguson et al., 1995; Koning et al., 2004a). Late-rift basalts flowed into a paleo-topographic low coinciding with the Velarde graben between 3 and 5 Ma (Koning et al., 2011; Repasch et al., 2018). Because these basalts are resistant to erosion, the paleo-topographic low is now a topographic high, coinciding with Black Mesa, due to exhumation that has occurred in this area since 3 million years ago.

Velarde graben

The 3D gravity bedrock-elevation model was heavily used for contouring the Velarde graben. This model suggests that the top-of-bedrock elevation in the deepest part of the Velarde graben is -2000 ft (below sea level), which translates to a depth (and basin fill thickness) of ~8,900 ft below the top of Black Mesa. The slightly lower Bouguer gravity anomalies towards the west side of the Black Mesa (Plate 1) suggest that the Velarde graben is asymmetric, with the deepest part toward it's the west side. In contrast, structural interpretations of Harper (2015) show a more symmetrical structure that is as deep as -3300 ft (below sea level), which gives a basin fill thickness of 10,200 ft. Given the 15% discrepancy of the depth (thickness) of basin fill in these two input data sets, one can infer a ~15-20% vertical error in the contouring of the top of the bedrock in the Velarde graben near the Black Mesa seismic reflection line.

Both the 3D gravity bedrock-elevation model and the Black Mesa seismic reflection line (Harper, 2015; Koning et al., 2013) indicate that the top of the bedrock has a southward component of dip under the northern part of Black Mesa, resulting in a maximum depth of the graben being near the middle of the mesa. The 3D gravity bedrock-elevation model indicates a south-dipping syncline between the West and East Black Mesa faults, which was mimicked in the contours of both the top of the bedrock and the base of the middle Santa Fe Group. However, gravity stations in this area are sparse and so the exact structural form here is uncertain. The southward dip of the top of the bedrock is about twice as much as the southward dip of the base of the middle Santa Fe Group.

West and East Black Mesa faults

Structural contouring of what was formerly called the Black Mesa fault (e.g., Koning et al., 2013; Kelson and Koning, 2015) indicates that the gradient in the 3D gravity bedrock-elevation model corresponding to the western margin of the Velarde graben does not coincide with this structure. The density of gravity stations near Black Mesa (Plate 1) gives confidence in this interpretation. Thus, a new fault was drawn on the maps (Plates 1–4) under the modern Rio Ojo Caliente floodplain, whose 65° E-dipping fault plane (dip magnitude inferred to be similar to that of nearby exposed faults) coincides with the steep gradient of the 3D gravity bedrock-elevation model. This new fault is named the West Black Mesa fault, whereas the former "Black Mesa fault" is renamed as the East Black Mesa fault. The maximum depth indicated by the 3D gravity bedrock-elevation model is located 0.3–0.6 mi southeast of the southern tip of the mapped trace of the East Black Mesa fault, which does not make geologic sense because the end of a fault zone should have minimal displacement. However, this maximum depth is near the center of the newly drawn West Black Mesa fault. Credit is given to John Ferguson, who was the first person to interpret a major east-down fault near the location of the West Black Mesa fault (J. Ferguson, personal communication, 2003).

La Mesita fault

The La Mesita fault strikes southwest through the center of the Velarde graben, producing a 200–230 ft vertical offset (down to northwest) of the 4.9–3.5 Ma basalt that caps La Mesita (age from Koning et al, 2013; Repasch et al., 2017) and a possible left-lateral displacement of 1500 ft (Koning and Aby, 2003; Aby and Koning, 2004; Koning et al., 2004a). The contouring suggests a relatively low throw range of 200–400 ft of the top of the bedrock for the northern La Mesita fault, but the specific magnitude is poorly constrained. Throw may possibly be greater on the southern La Mesita fault.

Velarde and Rio de Truchas faults

Two noteworthy faults extend southwestwards from the Embudo area: the Velarde fault to the west (10-mi long) and the Rio de Truchas fault to the east (5-mi long). The Velarde fault becomes the Dixon fault to the north (Koning and Aby, 2003; Plate 1). Based on this contouring effort, the Velarde fault has experienced about equal amounts of throw in the top-of-bedrock vs. the base-of-middle Santa-Fe-Group surfaces (Plate 4, 1000–1400 ft). However, the throw of the top of bedrock along the Rio de Truchas fault is about twice the magnitude than the throw of the base of the middle Santa Fe Group surface (1000 ft vs 400 ft), consistent with interpretations by Koning et al. (2013) of early rift rift activity along this fault. The true depth of the middle Santa Fe Group on the Velarde fault hanging wall is poorly constrained by analyses of the Rio de Truchas seismic line, so comparison of throw of the middle-Santa-Fe-Group base is uncertain.

Chamita syncline

At the south end of the Velarde graben lies an anomalous structure called the Chamita syncline (Figure 2; Koning et al., 2004a, 2011, 2013). Abundant, consistent stratal attitudes from geologic mapping (Koning and Manley, 2003; Koning et al., 2011) indicate that this syncline plunges westwards and has a slightly arcuate axial trace (concave to the south). Using these data to project the top of bedrock and base-of-middle-Santa-Fe-Group surfaces downwards towards the axis of the syncline results in a depth of the top of the bedrock that is notably greater than that indicated by the gravity inversion-based bedrock elevation model (-1400 to -1600 ft vs. -600 to -700 ft below sea level). The deeper projected depths were used to be consistent with the contouring guidelines, but it is worth noting that there is little justification in making the top of bedrock dip more steeply than the base of the middle Santa Fe Group along this structure.

Santa Clara graben

The deepest part of the Santa Clara graben is interpreted to lie 2.5–3 mi southeast of Cerro Roman. There, the 3D gravity bedrock-elevation model suggests that the top of the bedrock is about -3900 ft-elevation (below sea level). The structural contouring effort used this depth and followed the 3D gravity bedrock-elevation model. The Santa Clara graben is bound by the northeast-striking, southeast-down North Pajario fault on its extreme western side. This fault has offset the upper Bandelier Tuff (Tshirege Member) by 300-500 ft (Golombek, 1983; Kempter et al., 2005). A degraded fault scarp located 1.4 mi to the southeast of the North Pajarito fault, ~60–100 ft in height (southeast-side down), marks the southern strand of the Santa Clara fault. The north-striking, east-down Gaucho fault (following naming convention of Koning et al., 2013) lies near the east side of the Santa Clara graben. The Gaucho fault can be observed in outcrop and, like the Santa Clara fault, has produced surficial fault scarps. These scarps indicate east-down displacement and range from 0.9 to 3.1 mi in length. For the sake of simplicity, only the middle strand of the Gaucho fault was contoured (Plates 1–4). The Northern Pajarito fault is modeled as joining with the southeast-striking Cañada de Amagre fault, but it should be noted that the intersection of these two structures is uncertain.

In order to synthesize surface-based data with the 3D gravity bedrock-elevation model, the following throw magnitudes were used on the North Pajarito and southern Santa Clara faults for the top-of-bedrock contours: 2600 ft and 3600 ft. However, smaller throws were needed for the base-of-middle-Santa-Fe-Group surfaces: 300–400 ft and 1100 ft. Note that there is some degree of freedom on how to partition the throw of the base of the middle Santa Fe Group between the two faults (i.e., more throw could have given to the North Pajarito fault and less for the southern Santa Clara fault). Because of a lack of a gradient in the 3D bedrock-elevation model, the Gaucho fault does not appear to notably offset the top-of-bedrock surface. Thus, I modeled this fault as producing subequal throws of the base of the middle Santa Fe Group and top of bedrock, 600–800 ft, considerably less than the throw values on the North Pajarito and southern Santa Clara faults.

Initial geologic mapping (Koning et al., 2005a) inferred that a northwest-striking fault, running along the southern base of Cerro Roman, connected the North Pajarito and Santa Clara fault strands. However, in honoring the stratal attitudes there (30–50° south), the fault was found to be unnecessary; in fact, having a fault with notable throw (hundreds of ft or more) made contouring the general area too difficult. Thus, the area south of Cerro Roman is modeled as a south-dipping ramp, with both the top of bedrock and base of the middle Santa Fe Group having the same geometries (i.e., top of the bedrock does not dip more steeply than the base of the middle Santa Fe Group). Geologic mapping 0.6 to 0.9 mi east of Cerro Roman indicate that middle Santa Fe Group strata strike east-west and dip 20–25° to the north. This necessitated having a northeast-striking bedrock high on the immediate footwall of the Santa Clara fault at a location 1.1 mi southeast of Cerro Roman.

Between the Santa Clara and Velarde grabens

The area between the Santa Clara and Velarde grabens was somewhat difficult to contour. Stratal attitude data are not as consistent as elsewhere in the study area and many minor structures are present. South of the village of San Jose, stratal attitudes indicate northeast strikes, which were honored in the base-of-middle-Santa-Fe-Group contours. However, the 3D gravity bedrock-elevation model shows north-northwest strikes there, producing a discrepancy in strike between the top-of-bedrock and base-of-middle Santa Fe Group contours. About 2.5 mi west of San Jose, mapping suggests an anticlinal fold with an arcuate axis (concave to southwest), similar to the Chamita syncline fold axis. This fold was incorporated in the contouring. Some simplification was required 0.6 mi north of there to smooth out irregular surface stratal attitudes, producing a WNW, west-plunging synclinal structure 2.7 mi northwest of San Jose in both the top-of-bedrock and base-of-middle-Santa-Fe-Group contours. Although a structural low is required here in trying to rectify surface-based dips and faults with the 3D gravity model, the particular geometry and configuration of that structural low is uncertain.

Jemez Mountains

Contour surfaces in the Jemez Mountains include the base of Upper Miocene to Lower Pleistocene volcanic package in addition to the base of the middle Santa Fe Group and top of the bedrock. Near the Valles caldera, there is a paucity of gravity data and a breakdown of assumptions underlying the construction of the 3D gravity model (Grauch et al., 2009); this makes the utility of the 3D gravity model to map bedrock in this area is questionable. Thus, our top-of-bedrock surface contours are also highly uncertain (probably more than 30% error in vertical accuracy) under much of the Jemez Mountains (Plate 1).

The lack of subsurface data and outcrops in the area south of Santa Clara Canyon also impart high uncertainty in the base of volcanics and the base-of-middle-Santa-Fe-Group contours. There, I heavily followed the interpretations of the base of the Keres Group in Cole et al. (2009, unit tvk_bs). The result is a dome-like structural high in the headwaters of Puye Canyon for the top of bedrock, just east of the North Pajarito fault, which has flanks dipping off to the south, west, and northwest. The base of the volcanic rocks, however, is highest near Santa Clara Creek.

Confidence in structural contouring is somewhat higher in Santa Clara Canyon and much higher north of Santa Clara Canyon (Plates 1-3). Exposures about 0.6 mi east of the North Pajarito fault indicate northeast-striking strata dipping 10–12° NW. Based on these exposures, the contours are drawn to have a northeast stratal strike and a northwest dip in the vicinity of Santa Clara Canyon. North of Santa Clara Canyon, attitudes and map relations of geologic contacts impart a high degree of reliability to both the base-of-volcanics and base-of-middle-Santa-Fe-Group structural contours.

DISCUSSION

Age of structures

The 13–13.5 Ma age of the base-of-middle-Santa-Fe-Group surface (Koning and Aby, 2005; Koning et al., 2005, 2011, 2013) is about halfway through the rift's extensional history (assuming extension started at ~26–30 Ma per Koning et al., 2013, and Lipman and Mehnert, 1975). Thus, comparing the vertical offset of the base of the middle Santa Fe Group vs. that of the top of the bedrock would allow interpretation of the relative age of structures. For example, if the vertical offsets (throw) of both surfaces are approximately similar (within error), then one could infer that a given structure was primarily active after 13–13.5 Ma. If the top-of-bedrock surface is offset but not the 13–13.5 Ma base-of-Santa Fe Group surface, then the fault movement took place prior to 13–13.5 Ma. If the top-of-bedrock surface is offset about twice as much as the base-of-Santa Fe Group surface, then deformation along that structure was relatively constant throughout the rift's ~26 Ma history. However, if the top-of-bedrock surface is offset notably more than twice that of the base-of-middle-Santa–Fe-Group surface, then the primary period of fault activity occurred prior to 13–13.5 Ma but subordinate fault motion occurred subsequent to 13–13.5 Ma. This analysis assumes that the average extension rate between ~13 and 26 Ma is relatively similar to the average extension rate between ~13 Ma and present.

Table 2 lists the throw values of various faults using the vertical offset of the structural contours. However, error is not incorporated so any interpretations should be considered as preliminary and subject to change. Robust error calculations are dependent on site-specific factors, and a thorough analyses of fault activity using this technique is deferred to future work. In the faults that are listed, the base of the middle Santa Fe Group is constrained by: (1) stratal attitudes and the presence of the mapped contact on the hanging wall, and/or (2) drill-hole data.

Table 2. Fault throw data from structural contours and inferred age range of activity. Error not incorporated.

Structure and location	Throw of top of bedrock (ft)	Throw of base of middle Santa Fe Group (ft)	Likely primary period of activity (Ma)*
Ojo Caliente fault adjacent to deepest sub-basin in hanging wall	3200	800-900	Pre-13 Ma
Southernmost Ojo Caliente fault, south of Rio Ojo Caliente	800	1200	Post-13 Ma
Cañada del Amalgre fault, Rio del Oso**	1200	1300	Post-13 Ma
West Black Mesa fault, center (Vallito Peak)	5000	700	Pre-13 Ma
East Black Mesa fault, center (north edge of Black Mesa)	400	200	Continuous
Velarde fault, Rio de Truchas seismic line	1000	1300***	Post-13 Ma
Rio de Truchas fault, Rio de Truchas seismic line	1000	400	Continuous
Santa Clara fault, 1.9 mi SW of Rio Chama****	3000	1700	Continuous
Santa Clara fault, 2.5 mi SW of Rio Chama****	4000	2300	Continuous
Santa Clara fault, west side of Santa Clara graben	3600	1300	Continuous

Notes

*Tentative (preliminary) interpretation because error is not considered. Base of middle Santa Fe Group is 13-13.5 Ma (Koning et al., 2013), but simplified to 13 Ma in this table. Activity is considered to be pre-13 Ma if the throw of the top-of-bedrock surface is more than triple the throw of the base-of-middle-Santa-Fe-Group surface, post-13 Ma if throw is comparable within 30-50% error, and continuous if the top-of-bedrock surface has about twice the throw than the base-of-middle-Santa-Fe-Group surface. Note that structures in the Abiquiu embayment are interpreted to have experienced a dramatic slow-down in activity rates at around 10 Ma (Smith, 2004; Koning et al., 2016).
** Using geologic data in Koning et al. (2005a), the base of the middle Santa Fe Group projects to 7280 ft asl on the footwall.
***Middle Santa Fe Group base on hanging wall is poorly constrained
****Includes throw associated with monoclinal flexure

Preliminary age constraints of various structures are integrated in the rest of the Discussion section. Below, a summary of interpretations obtained from inspection of the structural contours are given, organized according to location.

Northeast of Española Basin and Laramide paleotopography

The northeast Española Basin is characterized by a broad, west-plunging syncline between the lower Santa Cruz River and the lower Rio Embudo, The north limb of the syncline exhibits northwest strikes and southwest dips; this geometry results in bedrock being exposed to the north near the Rio Embudo. The south syncline limb is characterized by northeast strikes that bend more northerly to the south, at a location 0.6-1.9 mi north of the Santa Cruz River. This bend to more northerly strikes creates a northwest-plunging anticline that projects to Ohkay Owingeh. These are considered high-confidence structural features due to good exposure, consistent stratal dips on the geologic maps, and the Rio de Truchas seismic reflection line (Fig. 2).

This stratal strike pattern is ascribed to changes in orientation of the master fault system and a northward decrease of uplift on the distal hanging wall ramp. The eastern Española Basin corresponds to a west-tilted, asymmetric basin (half-graben) tilted towards the Pajarito fault system (south of Española) and the Embudo fault system (north of Española) (Koning et al., 2013). The Santa Clara fault links the North Pajarito fault with the faults bounding the Velarde graben, with step-overs occurring between the south end of the Santa Clara fault and the north end of the Pajarito fault and also between the north end of the Santa Clara fault, the Guique fault, and the southern Velarde fault. The aforementioned, northwest-plunging anticline projects to where the middle of the Santa Clara fault changes overall strike from north-northeast (albeit with lots of jogs) to a more consistent northeast strike (north of the Rio Chama). The syncline axis approximately projects to the deepest part of the Velarde graben, with perhaps 0.6–1.2 mi of left-lateral offset across the La Mesita fault. Lastly, the northwest-striking, north limb of the syncline appears to continue westward past Embudo, where it becomes the northern structural ramp of the Velarde graben. Thus, the geometry and locations of two major structural features of the Embudo fault system, the Santa Clara fault and Velarde graben, can account for the synclinal structure northeast of Española. The structural relief on the south limb of the synclinal structure is amplified by an inferred northward decrease in uplift of the distal hanging wall of the eastern Española Basin half graben, as interpreted by Smith and Pazzaglia (1995) using the Borrego surface (see also Koning et al., 2013, p. 193). Furthermore, uplift along the Picuris Mountains amplifies the structural relief of the north limb of the synclinal structure.

A notable 30–40° discrepancy of strikes between the top-of-bedrock and base-of-middle-Santa Fe Group contours occurs between the Santa Cruz River and the Rio de Truchas (Plate 1). This lies in an area of relatively high certainty due to the presence of the Rio de Truchas seismic line and abundant stratal attitude data from geologic mapping. The 30–40° discrepancy is interpreted to be due to paleotopography that was present during the start of deposition of the Santa Fe Group. Specifically a Laramide paleo-highland having a northwest trend and a southwest-directed slope may be preserved in the subsurface. During the course of rifting, a general syncline developed in the Peñasco embayment that extended to the west. Folding on the south limb of the syncline rotated the top of the bedrock to have a northerly strike and the overlying Santa Fe Group strata to have a northeasterly strike.

Abiquiu embayment

The northwest part of the study area, northwest of the Embudo fault system, is called the Abiquiu embayment and corresponds to where the Santa Fe Group is relatively thin (compared to the western part of the eastern Española Basin half graben). In a structural sense, it has been described as a "shallow platform" by Baldridge et al. (1994). For the west edge of the study area near the Rio Chama, cross-sections in Baldridge et al. (1994) indicate a general thickness of the Santa Fe Group of 2000 ft and a basal elevation of about 4000 ft asl. Modeling of the top of the bedrock by Harper (2015, fig. 5.10) shows the base of the Santa Fe Group dipping east towards the Ojo Caliente fault, so that top of the bedrock is at about sea level on the immediate hanging wall of the fault (giving a Santa Fe Group thickness of about 6000 ft. However, the 3D gravity bedrock-elevation model suggests an elevation of 1000 ft asl and a corresponding Santa Fe Group thickness of ~5,000 ft. Note that I include the Abiquiu Formation in the Santa Fe Group (Fig. 3).

Although describing the Abiquiu embayment as a platform is appropriate in a broad sense, the platform is broken by numerous mapped faults. Along-strike displacement gradients along these faults have created sub-basins on the immediate hanging walls of the major faults. Specific values of top-of-bedrock elevations and basin fill depths are noted in the Results section. Where the top of the bedrock is interpreted to be deepest, coinciding with these sub-basins, the Ojo Caliente Sandstone is preserved. This indicates that tectonic subsidence and related faulting in the Abiquiu embayment was active after the 13.5 Ma base of the Ojo Caliente Sandstone (age from Koning et al, 2013). The total structural relief of the top of the bedrock is about 1000 to 2000 ft, whereas the relief of the base of the middle Santa Fe Group is typically closer to 500–600 ft. Thus, activity on the structures occurred prior to 13–13.5 Ma as well as after 13–13.5 Ma (probably mostly within 13–10 Ma, based on interpretations by Smith, 2004, and Koning et al., 2016), consistent with the preliminary fault activity interpretations of Table 2.

Peñasco Basin

A relatively deep basin containing a 2200-2600 ft thickness of Santa Fe Group basin fill is interpreted east of Peñasco (Plate 1). The basin is inferred to be synclinal, with an east-west axis, based on the 3D gravity bedrock-elevation model and our contouring. Whether this syncline plunges east or west is uncertain. Based on geologic map data, the deepest part of this basin may be on the east end, immediately adjacent to the northern Peñasco fault. Relative uplift of the Picuris Mountains apparently created a south-dipping ramp on the north side of this basin.

Embudo fault system and Velarde graben

The Embudo fault system includes several faults. The variably northeast-striking to north-striking Santa Clara fault appears to link (via a step-over) the Northern Pajarito fault with faults associated with the Velarde graben. The La Mesita fault projects southwestward through the center of the Velarde graben. Bounding the west side of the graben is the West Black Mesa faults, and bounding the east side of the graben is the Velarde fault.

Close comparison of Bouguer anomaly gravity data with what was formerly called the Black Mesa fault (cf. maps of Koning et al., 2013) indicates the need for a large vertical displacement fault to the west of that fault. This report refers to the former Black Mesa fault as the East Black Mesa fault, and the newly recognized fault as the West Black Mesa fault. The location and dip (65° east) of the East Black Mesa fault are well-constrained because the fault makes a prominent scarp on Black Mesa and exposures of the fault plane are visible north of Black Mesa. Using these data to contour the corresponding fault plane indicates that there is no gravity gradient corresponding to the eastward, down-dip projection of the fault plane of the East Black Mesa fault. In contrast, the lower range of Bouguer anomaly data (-256 to -257 mgals) observed in the area (Bouguer data is presented in Plate 1), spanning a NW-SE width of 2.1 mi, extend to within 330 ft east of the mapped surficial trace of the East Black Mesa fault. However, a very steep gradient is present within a northeast-trending, 0.6 mi-wide zone situated to the northeast East Black Mesa fault and southeast of the Rio Ojo Caliente. This gradient is mimicked in the 3D gravity elevation-model (see ArcGIS database). The change in the Bouguer anomaly values over this 0.6 mi-wide zone is 10 mgals, whereas the change in Bouguer anomaly for the 2 mi east of the East Black Mesa fault is only about 1 mgal. Given the lack of a gravity gradient corresponding with the East Black Mesa fault plane, I mapped a new fault, the West Black Mesa fault, under the Rio Ojo Caliente valley because its subsurface fault plane would coincide with the 10 mgal-gravity gradient (assuming a 65 degree eastward dip). This newly mapped fault was first hypothesized by John Ferguson (pers. communication, 2003).

The newly named West Black Mesa fault has about 4500-5,000 ft of throw of the top-of-the-bedrock contours, consistent with interpretations in Koning et al. (2013). Based on the aforementioned gravity gradient, this fault strikes parallel to the trend of the lower Rio Ojo Caliente and the west edge of Black Mesa. Early Pliocene movement along the West Black Mesa fault probably exerted a fundamental control on the western paleovalley margin associated with the paleotopographic depression into which the Servilleta Basalts flowed. Exactly where the West Black Mesa fault terminates to the north is uncertain. To the south, the West Black Mesa fault is inferred to terminate against the Ojo Caliente fault. Possibly, the west-down movement along the southern Ojo Caliente fault offset the southernmost tip of the West Black Mesa fault to the north by 0.6–0.9 mi; the northeastward striking top-of-bedrock structural contours just north of the mouth of the Rio del Oso may coincide with this apparent lateral offset. If so, surface-based geologic data (map relations, stratal attitudes) and our contouring effort does not suggest that the West Black Mesa fault continues more than ~1 mi southwest of the Ojo Caliente fault.

The geologic structure near the intersection of Rio Ojo Caliente, Rio del Oso, and the Rio Chama is complex. It is difficult to have another solution to the data constraints (stratal dips, Rio del Oso seismic reflection line, stratigraphic unit distribution, and 3D gravity model) other than to have a structural low on the immediate southwest side of the southernmost Ojo Caliente fault.

Bouguer gravity data indicate a more notable gradient along the southern West Black Mesa fault compared to the southern Ojo Caliente fault. This is reflected in our top-of-bedrock contouring by the ~5000 ft of throw on the West Black Mesa fault vs. 600–800 ft of west-down throw of this surface along the southernmost Ojo Caliente fault (south of the West Black Mesa fault). North of the fault intersection, however, 2400–3000 ft of west-down throw on the Ojo Caliente fault is inferred.

Based on this model of drawing the structural contours, one could possibly infer that the Ojo Caliente fault grew southwards, intersected and offset the southernmost West Black Mesa fault, and after this intersection event the two faults accumulated similar strain relatively concurrently over significant amounts of time (probably several millions of years). Continued southward growth of the southernmost Ojo Caliente fault, south of the fault intersection, progressed to the Santa Clara fault but only resulted in relatively minor throw (600–800 ft based on the contouring) of the top-of-bedrock surface. It should be noted that in honoring the geologic map stratal attitude data, there is more throw (1000–1200 ft vs 600–800 ft) for the base of the middle Santa Fe Group unit than top of the bedrock along the southernmost Ojo Caliente fault (south of the fault intersection). This violates the guideline constraints discussed in the Methods section, but it should be noted that the discrepancy lies within the 30-50% estimated vertical margin of error discussed above. In reality there is likely subequal displacement of both the top-of-bedrock and base-of-middle-Santa-Fe-Group surfaces on the southernmost Ojo Caliente fault (south of the intersection with the West Black Mesa fault). If so, then displacement along the southernmost Ojo Caliente fault south of the West Black Mesa fault post-dates 13–13.5 Ma. This would also explain why both the top-of-bedrock and Santa Fe Group reflectors in the Rio del Oso seismic line, located on the hanging wall of the southernmost Ojo Caliente fault, are relatively parallel to one another (Ferguson et al., 1995, fig. 2).

The Velarde graben is a fault-bounded structure. As discussed above, the West Black Mesa fault is the major bounding structure of the western margin of the Velarde graben, where the contouring effort suggests about 4500–5000 ft of throw as opposed to 200 ft of throw on the East Black Mesa fault. On the east side of the Velarde graben, the Velarde fault is the major bounding structure. Preliminary analyses based on the contouring indicates the Velarde fault has offset the top of the bedrock by ~1000 ft and the base of the middle Santa Fe Group by 1000–1200 ft

(Table 2), but offset of the latter is poorly constrained at present. The possible comparable offset of the two surfaces would suggest that movement along the Velarde fault postdates the 13–13.5 Ma base of the middle Santa Fe Group. The Rio de Truchas fault vertically offsets the top of the bedrock by 1000 ft and the base of the Santa Fe Group by 400 ft, indicating this fault has a relatively long displacement history, consistent with Koning et al., (2013).

In addition to likely left-lateral slip (see Koning et al., 2004, 2013, and Bauer and Kelson, 2004), there is a drop of Bouguer gravity values westward across the trace of the La Mesita fault near Velarde (from -252 to -250 on east side to -255 to -257 on west side). The structural contouring is poorly constrained for the La Mesita fault (thus it is not listed on Table 2), but this structure appears to vertically offset both the top-of-bedrock surface and the base-of-middle-Santa-Fe-Group surface by about 300-600 ft. This amount of throw is about double the 200-230 ft of throw on the fault calculated from vertical offset of the 3.5–4.9 Ma Servilleta Basalts on La Mesita (ages from Repasch et al., 2017, and Koning et al., 2013), suggesting relatively continuous slip rates for the roughly 4-5 million years preceding and postdating the emplacement of these basalts.

There is a ~1 mi rightward step between the south end of the La Mesita fault and the north end of the Santa Clara fault. The La Mesita fault has northwest-down throw (based on geologic mapping near Velarde) whereas the Santa Clara fault exhibits southeast-down throw. For the practical purposes of modeling the Embudo fault system as a barrier in the groundwater model (built from Intera's geologic model), a vertical 080 degree striking, hypothetical fault was drawn connecting the ends of these oppositely dipping faults (labeled on Plates 1-4). However, a field visit to this critical area confirmed that the northeast-striking, hard-linkage fault does not exist. Rather, the faults in the area are relatively small and strike either 345° or 020°. The northeast-striking faults exhibit left-lateral slip and the northwest-striking faults display mostly right-lateral slip. Thus, this step-over area is characterized by strain distributed over small NE and NW trending faults. Right-lateral slip along the northwest striking faults likely accommodates the 11.5° of counter-clockwise rotation interpreted here by Brown and Golombek (1985).

Several consistent attitudes on the north limb of the Chamita syncline indicate 4–25°south dips in the step-over area, increasing to the west. However, there is no corresponding gradient in the Bouguer anomaly data — but there is a paucity of gravity stations in this area. The south dips in exposed strata extend west of the north end of the Santa Clara fault and create 5° south dips in the 3.6 Ma Sevilleta Basalt capping Black Mesa (age from Koning et al., 2013). As noted earlier, the Chamita syncline has been inferred to be a transpressional feature related to the right step between the La Mesita fault and the Santa Clara fault (Koning et al., 2011, 2013).

A major discrepancy exists between the top-of-bedrock structural contours, as just described, and the base-of-middle-Santa-Fe-Group contours. Following the gravity data and the 3D gravity bedrock-elevation model, the top-of-bedrock contours strike northeast parallel to the major faults and 800 ft of northwest-down throw on the south end of the La Mesita fault was modeled. Using attitudes measured on the west flank of Black Mesa, the top of the bedrock strikes north to northeast under the west side of Black Mesa. To draw the base-of-middle Santa Fe Group surface, both the middle Santa Fe Group stratal attitudes and the structures that deform the Servilleta Basalt were used. But this results in the strikes of the two contour sets being orthogonal to each other in a manner that does not make geologic sense. This is likely a "red flag" that there is inadequate understanding of the Chamita syncline.

This project artificially required the Embudo fault to be a through-going feature for Intera's simplified groundwater model, and the structural contours near the Chamita syncline partly reflect this simplification. In actuality, the La Mesita fault likely ties with the Guique fault or closely parallels it ~1600 ft to the west. The northernmost Santa Clara fault is probably a minor structure *per se*, and the structural strain is mostly manifested by tilting of strata. The contour model of this effort is probably adequate on the south limb of the syncline. But on the north limb the bedrock contours (especially -800 to -1600 bsl) should extend parallel with the base-of-middle Santa-Fe-Group contours to tie into the equivalent contour lines to the west. Thus, there would be a true basement high just north of the Chamita syncline corresponding to the -254 to -255 mgal Bouguer anomaly data (Bouguer data presented in Plate 1). Furthermore, the anticlinal structure modeled west of the south end of the Velarde fault and the small, east-tilted half-graben on the immediate hanging wall of the southern fault could be eliminated because they are not supported by the Bouguer gravity data. In addition to the structural high northeast of the north end of the Santa Clara fault, block rotation within the Chamita syncline area can help accommodate transfer of strain across the right step-over between the Velarde-Guique-La Mesita faults and the Santa Clara faults, with shearing along the NW-orientated, dextral-slip faults facilitating the counter-clockwise rotation interpreted by Brown and Golombek (1985).

Gravity data is sparse over much of the Chamita syncline, making interpretations regarding the specific elevation of top of the bedrock uncertain. However, with the available data used to create the 3D gravity bedrock-elevation model, the top-of-bedrock surface cannot be notably steeper than the base-of-middle-Santa-Fe-Group surface. Thus, the Chamita syncline, together with the Velarde and La Mesita faults, are inferred to be post-13–13.5 Ma structures directly related to lateral movement along the Embudo fault system.

Santa Clara graben and Santa Clara fault

Contours in the Santa Clara graben have more uncertainty than in the Velarde graben due to a lack of published seismic lines. Decent exposure of Upper Miocene sediment in the wedge-like, structural low extending parallel (east of) the Santa Clara fault northeast of Cerro Roman suggest transverse-orientated folds that were previously interpreted to be related to transpression (Koning et al., 2013). Like the northeast Española basin, there is a discrepancy between the strikes suggested by the top-of-bedrock contours and the base-of-middle-Santa-Fe-Group contours, perhaps reflecting paleotopography inherited from the Laramide orogeny.

Strain along the Santa Clara fault is partitioned between monoclonal flexure and discrete fault offset. In the following, we incorporate the collective vertical displacement of these two strain features. A southward-increasing displacement gradient on the Santa Clara fault is required to construct geologically reasonable contours. Immediately south of the Rio Chama, there is minimal displacement of the base of the middle Santa Fe Group and 1400 ft of throw of the top of the bedrock. But 2.5 mi to the southwest, there is 4000 ft of throw of the top of the bedrock and 2300 ft of throw of the base of the middle Santa Fe Group. On the western margin of the Santa Clara graben, there is 3600 ft of throw of the top of the bedrock and 1300 ft of throw of the base of the middle Santa Fe Group along the Santa Clara fault. These throw values are relatively uncertain and robust analysis of errors has yet to be conducted, but taking the contour model at face-value would indicate a factor of two difference between the two surfaces along the fault, suggesting that the Santa Clara fault and the Santa Clara graben have been active throughout rifting.

The Gaucho fault appears to converge northward into and interact with the Santa Clara fault. Vertical offset along the Gaucho fault is not apparent in gradients of the Bouguer gravity anomaly data or the 3D gravity bedrock-elevation model. The amount of throw suggested by offset of the base of the middle Santa Fe Group (400 ft) is sufficiently low that it may not be reflected in gravity data, and thus a throw of 400 ft was assigned for the displacement of the top of the bedrock. This modeling is poorly constrained, but would require the Gaucho fault to be a relatively minor structure that moved primarily after 13–13.5 Ma.

It is noteworthy to compare the throw values of the two major faults in the northwest part of the Santa Clara graben. The structural contouring effort for the top of the bedrock results in 2400–2600 ft of throw along the North Pajarito fault and 3600 ft of throw along the Santa Clara fault; the area in-between is a southeast (12–13°) dipping homocline. Where the Santa Clara fault bends 1.2 mi southeast of Cerro Roman, 6400 ft of top-of-bedrock throw is inferred along the Santa Clara fault (including stratal folding). However, only 2300 ft of throw of the base of the middle Santa Fe Group is required. In addition, a larger decrease in Bouguer gravity data values occurs across the Santa Clara fault compared to the Pajarito fault. Correspondingly, the 3D gravity bedrock-elevation model has 2500-3000 ft of throw along the Santa Clara fault and ~600 ft of throw along the North Pajarito fault. Thus, the southern Santa Clara fault may be equally as important, if not more so, than the North Pajarito fault in the tectonic development of the Santa Clara graben.

Tectonic Implications

The preliminary fault activity inferences discussed above are consistent with previous interpretations (Koning et al., 2004, 2016) regarding evolution of strain transfer across the left-stepping southern San Luis Basin and the northern Española Basin. Prior to 10-13 Ma, the Velarde graben acted as a pull-apart graben in a west-east regional stress field, very likely tilted westward towards the West Black Mesa fault, and was structurally isolated from the Santa Clara graben to the south. Eventually, evolution and growth of the Embudo fault system created a continuous fault system, probably ca. 10-12 Ma, between the southern San Luis Basin and northeastern Española Basin. Subsequently, left-oblique strain was focused on the Velarde, La Mesita, Guique, and Santa Clara faults, and the primarily normal-slip West Black Mesa and Ojo Caliente faults experienced a dramatic decrease in throw rates.

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REFERENCES

Aby, S.B., and Koning, D.J., 2004, Sedimentology of the Tesuque Formation and tectonics of the Embudo fault system near Dixon, New Mexico, in Brister, B.S., Bauer, P.W., Read, A.S., and Lueth, V.W., eds., Geology of the Taos Region: New Mexico Geological Society, 55th Annual Field Conference Guidebook,, p. 251–258.

Aby, S., and Timmons, J.M., 2005, Geologic map of the El Valle 7.5-minute quadrangle: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 105, scale 1:24,000

Baldridge, W.S., Ferguson, J.F., Braile, L.W., Wang, B., Eckhardt, K., Evans, D., Schultz, C., Gilpin, B., Jiracek, G., and Biehler, S., 1994, The western margin of the Rio Grande Rift in northern New Mexico: An aborted boundary?: Geological Society of America Bulletin, v. 105, p. 1538–1551.

Bauer, P.W, Helper, M.A., and Aby, S.B., 2005a (last modified April-2017), Geologic map of the Trampas 7.5-minute quadrangle, Taos County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 104, scale 1:24,000.

Bauer, P.W., Kelson, K.I., and Aby, S.B., 2005b, Geologic map of the Peñasco 7.5-minute quadrangle, Taos County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 62, scale 1:24,000.

Biehler, S., Ferguson, J., Baldridge, W.S., Jiracek, G.R., Aldren, J.L., Martinez, M., Fernandez, R., Romo, J., Gilpin, B., Braile, L.W., Hersey, D.R., Luyendyk, B.P., and Aiken, C.L., 1991, A geophysical model of the Española basin, Rio Grande rift, New Mexico: Geophysics, v. 56, p. 340-353.

Brown, L.L., and Golombek, M.P., 1985, Tectonic rotations within the Rio Grande rift: Evidence from paleomagnetic studies: Journal of Geophysical Research, vol. 90, No. B1, p. 790–802.

Cole, G., Coblentz, D., Jacobs, E., Koning, D., Broxton, D., Vaniman, D., Goff, F., and WoldeGabriel, G., Simmons, A., and Heikoop, J., 2009, The 2009 three-dimensional, geologic models of the Los Alamos National Laboratory Site, southern Española Basin, and Española Basin: Los Alamos Naitonal Laboratory, Report LA-UR-09-3701.

Ferguson, J.F., Baldridge, W.S., Braile, L.W., Biehler, S., Gilpin, B., and Jiracek, G.R., 1995, Structure of the Española Basin, Rio Grande Rift, New Mexico, from SAGE seismic and gravity data: New Mexico Geological Society Guidebook, 46th Field Conference, Geology of the Santa Fe Region, p. 105–110.

Golombek, M.P., 1983, Geology, structure, and tectonics of the Pajarito fault zone in the Española Basin of the Rio Grande rift, New Mexico: Geological Society of America Bulletin, v. 94, p. 192–205.

Grauch, V.J.S., Phillips, J.D., Koning, D.J., Johnson, P.S., and Bankey, V., 2009, Geophysical interpretations of the southern Española Basin, New Mexico, that contribute to understanding its hydrogeologic framework: U.S. Geological Survey Professional Paper 1761, 88 p.

Harper, C., 2015, Geophysical investigations of the Española Basin, Rio Grande rift, northern New Mexico [M.S. thesis]: University of Texas at Dallas, 67 p.

Kelley S.A., McIntosh, W.C., Goff, F., Kempter, K.A., Wolff, J.A., Esser, R., Braschayko, S, Love, D., and Gardner, J.N., 2013, Spatial and temporal trends in pre-caldera Jemez Mountains volcanic and fault activity: Geosphere, vol, 9, no. 3, p. 614–646.

Kelson, K.I., and Koning, D.J., compilers, 2015, Fault number 2006, Black Mesa fault zone, *in* Quaternary fault and fold database of the United States: U.S. Geological Survey website, https://earthquakes.usgs.gov/hazards/qfaults, accessed 12/26/2019.

Kempter, K.A., Kelley, S., Gardner, J., Reneau, S., Broxton, D., Goff, F., Levine, A., and Lewis, C., 1998 (last modified 16 Dec 2011), Geologic map of the Guaje Mountain quadrangle, Los Alamos and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 55, scale 1:24,000.

Kempter, K.A., Kelley, S., Koning, D., Ferguson, C., Osburn, B., and Fluk, L., 2005, Preliminary geologic map of the Vallecitos 7.5-minute quadrangle, Rio Arriba and Sandoval Counties, New Mexico, New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 108, scale 1:24,000.

Koning, D.J., 2002, revised July-2005, Geologic map of the Española 7.5-minute quadrangle, Rio Arriba and Santa Fe counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 54, scale 1:24,000.

Koning, D.J., 2003, revised 2005, Geologic map of the Chimayó 7.5-minute quadrangle, Rio Arriba and Santa Fe counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 71, scale 1:24,000.

Koning, D.J., 2004, Geologic map of the Lyden 7.5-minute quadrangle, Rio Arriba and Santa Fe counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 83, scale 1:24,000.

Koning, D.J., and Manley, K., 2003, revised December-2005, Geologic map of the San Juan Pueblo 7.5-minute quadrangle, Rio Arriba and Santa Fe counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 70, scale 1:24,000.

Koning, D.J., and Aby, S., 2003, Geologic map of the Velarde 7.5-minute quadrangle: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 79, scale 1:24,000.

Koning, D.J., and Aby, S.B., 2005, Proposed Members of the Chamita Formation, north-central New Mexico; New Mexico Geological Society, 56th Field Conference Guidebook, Geology of the Chama Basin, p. 258–278.

Koning, D.J., Nyman, M., Horning, R., Eppes, M., and Rogers, S., 2002, revised June-2005, Geology of the Cundiyo 7.5-min. quadrangle, Santa Fe County, New Mexico, New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 56, scale 1:24,000.

Koning, D.J., Ferguson, J.F., Paul, P.J., and Baldridge, W.S., 2004a, Geologic structure of the Velarde graben and southern Embudo fault system, north-central N.M.: New Mexico Geological Society, 55th Field Conference Guidebook, Geology of the Taos Region, p. 158–171.

Koning, D.J., May, J., Aby, S., and Horning, R., 2004b, Geologic map of the Medanales 7.5-minute quadrangle: Bureau of Geology and Mineral Resources, Open-file Geologic Map 89, scale 1:24,000.

Koning, D.J., Skotnicki, S., Moore, J., and Kelley, S., 2005a, Geologic map of the Chili 7.5-minute quadrangle, Rio Arriba county, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 81, scale 1:24,000.

Koning, D., Karlstrom, K., May, J., Skotnicki, S., Horning, R., Newell, D., and Muehlberger, W.R., 2005b (last modified 05-May-2011), Geologic map of the Ojo Caliente 7.5-minute quadrangle, Rio Arriba and Taos Counties, New Mexico: Bureau of Geology and Mineral Resources, Open-file Geologic Map 101, scale 1:24,000.

Koning, D.J., Connell, S.D., Morgan, G.S., Peters, L., and McIntosh, W.C., 2005c, Stratigraphy and depositional trends in the Santa Fe Group near Española, north-central New Mexico: tectonic and climatic implications, in Lucas, S.G., Zeigler, K.E., Lueth, V.W., and Owen, D.E., eds., Geology of the Chama Basin: New Mexico Geological Society, 56th Annual Field Conference Guidebook, p. 237–257.

Koning, D.J., Peters, L., Kelley, S., and McIntosh, W.C., 2007a, Evidence for rhyo-dacitic volcanism in the northern Jemez Mountains at 11–13 Ma [non-peer-reviewed mini-paper]: New Mexico Geological Society Guidebook, 58th Field Conference Guidebook, Geology of the Jemez Mountains Region II, p. 39–41.

Koning, D.J., Aby, S., and Kelson, K., 2007b, Geologic map of the Taos Junction quadrangle, Taos County, New Mexico: New Mexico: Bureau of Geology and Mineral Resources, Open-file Geologic Map 144, scale 1:24,000.

Koning, D.J., Smith, G.A., and Aby, S., 2008, Geologic map of the El Rito 7.5-minute quadrangle, Rio Arriba County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 166, scale 1:24,000.

Koning, D.J., McIntosh, W., and Dunbar, N., 2011, Geology of southern Black Mesa, Española Basin, New Mexico: new stratigraphic age control and interpretation of the southern Embudo fault system of the Rio Grande rift, in Koning, D.J., Karlstrom, K.E., Kelley, S.A., Lueth, V.W., and Aby, S.B., eds., Geology of the Tusas Mountains and Ojo Caliente Area: New Mexico Geological Society, 62nd Annual Field Conference Guidebook, p. 191–214.

Koning, D.J., Grauch, V.J.S., Connell, S.D., Ferguson, J., McIntosh, W., Slate, J.L., Wan., E., and Baldridge, W.S., 2013, Structure and tectonic evolution of the eastern Española Basin, Rio Grande rift, north-central New Mexico, in Hudson, M., and Grauch, V.J.S., eds., New Perspectives on the Rio Grande rift: From Tectonics to Groundwater: Geological Society of America, Special Paper 494, p. 185–219, doi:10.1130/2013.2494(08).

Koning, D.J., Baldridge, W.S., Ferguson, J.F., 2016, Deciphering a structural change at 11 Ma in the evolution of a classic transfer fault zone, the southern Embudo fault system in north-central New Mexico: Geological Society of America Abstracts with Programs, vol. 48, no. 7, Paper No. 54-6.

Lipman, P.W., and Mehnert, H.H., 1975, Late Cenozoic basaltic volcanism and development of the Rio Grande depression in the southern Rocky Mountains, in Curtis, B.F., ed., Cenozoic history of the Southern Rocky Mountains: Geological Society of America Memoir 144, p. 119–154.

Manley, K., 1976, The Late Cenozoic History of the Española Basin, New Mexico [Ph.D. thesis]: University of Colorado, 1–171 p.

Manley, K., 1979, Stratigraphy and structure of the Española basin, Rio Grande rift, New Mexico, in Riecker, R.E., ed., Rio Grande rift,: Tectonics and Magmatism: Washington, D.C., American Geophysical Union, p. 71–86.

Myer, C., and Smith, G.A., 2006, Stratigraphic analysis of the Yates #2 La Mesa well and implications for southern Española Basin tectonic history: New Mexico Geology, vol. 28, no. 3, p. 75–83.

Repasch, M., Karlstrom, K., Heizler, M., and Pecha, M., 2017, Birth and evolution of the Rio Grande fluvial system in the past 8 Ma: Progressive downward integration and the influence of tectonics, volcanism, and climate: Earth-Science Reviews, v. 168, p. 113–164, doi: 10.1016/j.earscirev.2017.03.003.

Smith, G.A., 2004, Middle to late Cenozoic development of the Rio Grande rift and adjacent regions in northern New Mexico, in Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico, A Geologic History: New Mexico Geological Society, Special Publication 11, p. 331–358.

Smith, G.A., and Pazzaglia, F.J., 1995, The Pliocene(?) Borrego pediment surface and development of the western Sangre de Cristo Mountains front [non peer-reviewed mini-paper], in Bauer, P.W., Kues, B.S., Dunbar, N.W., Karlstrom, K.E., and Harrison, B., eds., Geology of the Santa Fe Region: New Mexico Geological Society, 46th Annual Field Conference Guidebook, p. 6–8.

Smith, G.A., Timmons, J.M., and Gaud, M.N., 2004, Geologic map of the Truchas 7.5-minute quadrangle: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 84, scale 1:24,000.

FIGURES

Figure 1 (next page). Map showing geographic features and the final boundary (thick, purple line) of a geologic framework model constructed by Intera, Inc, to be incorporated into a groundwater model being jointly developed by the U.S. Department of Interior (Bureau of Indian Affairs) and the New Mexico Office of the State Engineer. The orange line denotes the northern boundary of their previous geologic model (immediately prior to this project). The thinner, pink line denotes the study area of this open-file report, where three stratigraphic surfaces were contoured; the pink line coincides with the extent of the top-of-bedrock structural contours. The yellow-shaded area depicts a region where previous contours were adjusted to achieve edge-matching (i.e., the structural contours of Cole et al., 2009, and the top-of-bedrock contours of the previous geologic model).

Figure 1

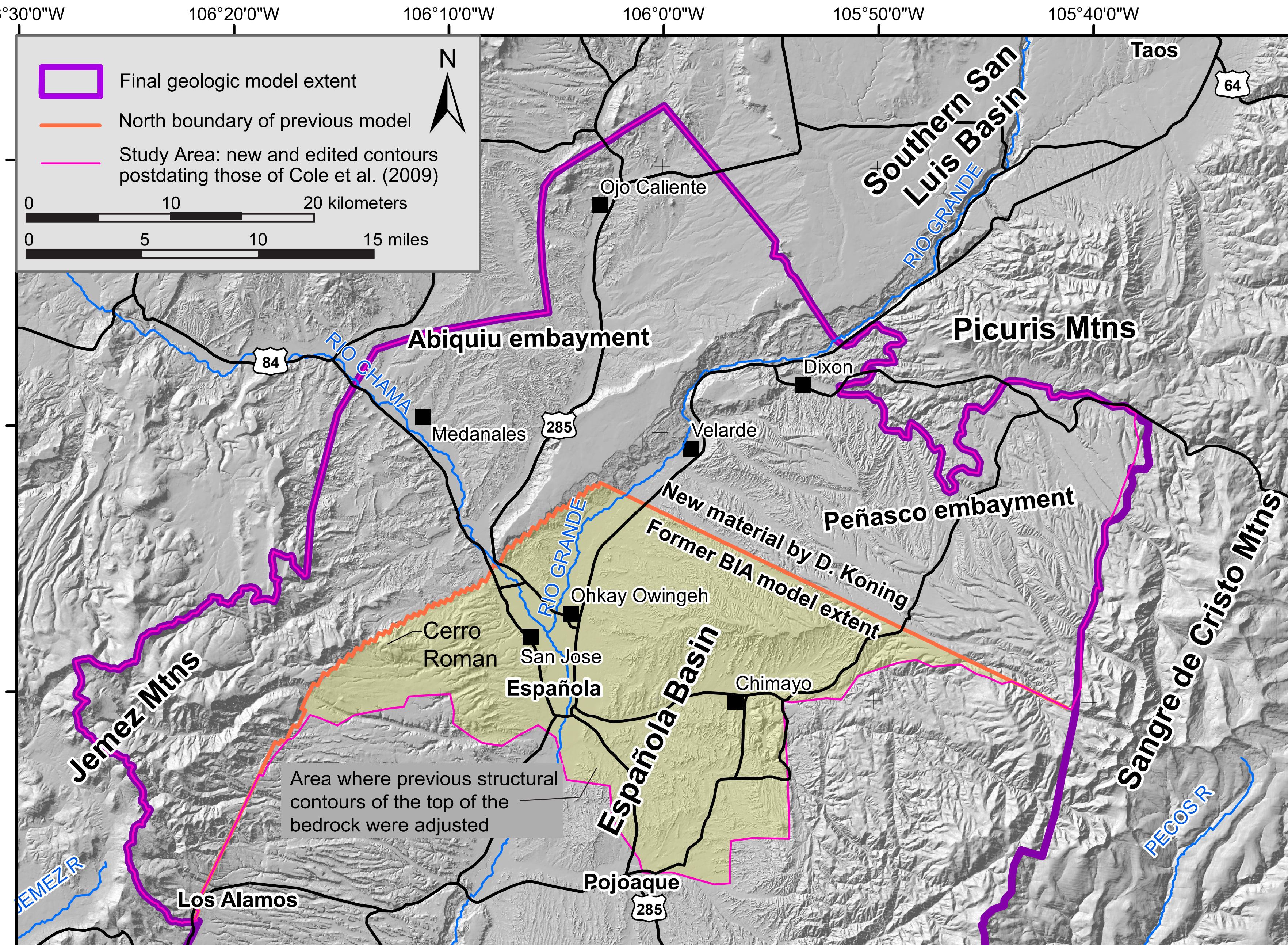
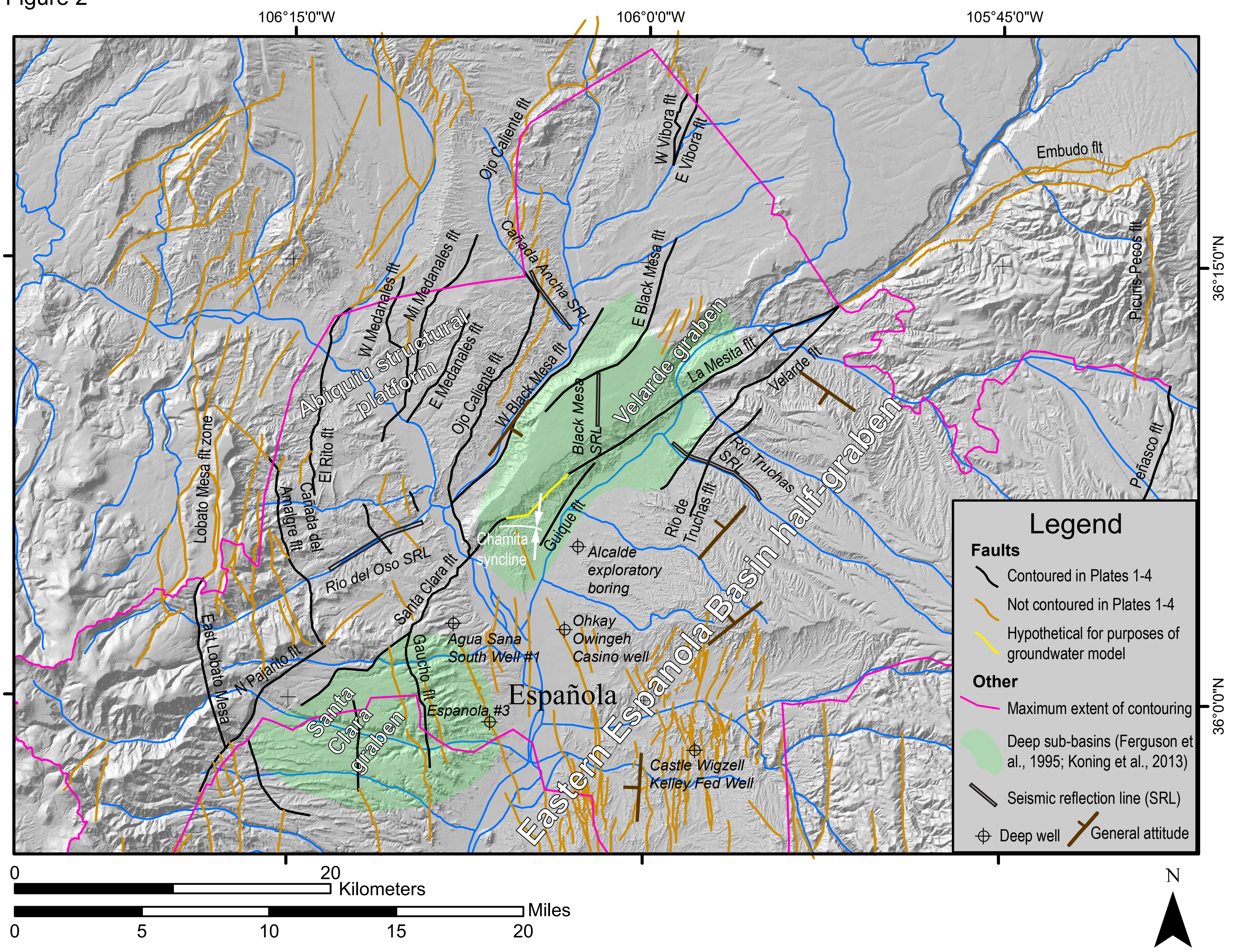

106°30'0"W
106°20'0"W
106°10'0"W
106°0'0"W
105°50'0"W
105°40'0"W
36°20'0"N
36°10'0"N
36°0'0"N
Final geologic model extent
North boundary of previous model
Study Area: new and edited contours postdating those of Cole et al. (2009)
N
0 10 20 kilometers
0 5 10 15 miles
Taos
64
Southern San Luis Basin
RIO GRANDE
Ojo Caliente
Picuris Mtns
Abiquiu embayment
RIO CHAMA
84
Dixon
Medanales
285
Velarde
Peñasco embayment
New material by D. Koning
Former BIA model extent
Sangre de Cristo Mtns
Ohkay Owingeh
Cerro Roman
San Jose
Española
Española Basin
Chimayo
Jemez Mtns
Area where previous structural contours of the top of the bedrock were adjusted
PECOS R
JEMEZ R
Los Alamos
Pojoaque
285

Figure 2 (next page). Notable structural features in the study area (denoted by the pink line). Note that the entire study area extent is not shown here (but is in Fig. 1). Major grabens (white, bold text) include the eastern Española half-graben (Koning et al., 2013) that lies east of the Embudo fault system (Santa Clara, La Mesita, Guique, and Velarde faults), the Santa Clara graben southwest of Española, and the Velarde graben north of Española. The asymmetric (west-tilted) Santa Clara graben is bounded on the west by the Santa Clara and North Pajarito faults. The Velarde graben is bounded by the West Black Mesa fault on the west and the Velarde fault on the east. Faults that were directly contoured in Plates 1–4 are in black; otherwise faults are shown in orangish brown. The yellow line near the Chamita syncline (white line) denotes a hypothetical fault that was contoured in order to achieve a continuous Embudo fault system that could be modeled as a fault barrier in the final groundwater model; in actuality, there is no such fault as shown but rather many small, northeast- and northwest-striking faults (Koning and Manley, 2003).

Figure 2



106°15'0"W
106°0'0"W
105°45'0"W
36°15'0"N
36°0'0"N
Legend
Faults
Contoured in Plates 1-4
Not contoured in Plates 1-4
Hypothetical for purposes of groundwater model
Other
Maximum extent of contouring
Deep sub-basins (Ferguson et al., 1995; Koning et al., 2013)
Seismic reflection line (SRL)
Deep well
General attitude
Embudo flt
Picuris-Pecos flt
Peñasco flt
W Vibora flt
E Vibora flt
Ojo Caliente flt
Cañada Ancha SRL
E Black Mesa flt
W Black Mesa flt
Black Mesa SRL
Velarde graben
La Mesita flt
Velarde flt
Rio Truchas SRL
Rio de Truchas flt
Abiquiu structural platform
W Medanales flt
Mi Medanales flt
E Medanales flt
El Rito flt
Cañada del Amalgre flt
Lobato Mesa flt zone
Rio del Oso SRL
Chamita syncline
Guique flt
Alcalde exploratory boring
Ohkay Owingeh Casino well
Agua Sana South Well #1
Santa Clara flt
Gaucho flt
Espanola #3
Española
N Pajarito flt
East Lobato Mesa
Santa Clara graben
Eastern Espanola Basin half-graben
Castle Wigzell Kelley Fed Well
0
20
Kilometers
Miles
5
10
15
N

Figure 3. Stratigraphy and the major stratigraphic units considered in this report: Upper Miocene-lower Pleistocene volcanic rocks, middle Santa Fe Group, lower Santa Fe Group, and bedrock. The structural contours coincide with the top of bedrock (same as the base of the lower Santa Fe Group), the base of the middle Santa Fe Group, and the base of the upper Miocene-lower Pleistocene volcanic rocks. Mafic rocks were not contoured where less than about ~100 ft thick.