PRELIMINARY STUDY OF THE GEOLOGIC FRAMEWORK OF THE COLORADO PLATEAU–MIDDLE RIO GRANDE BASIN TRANSITION, NEW MEXICO

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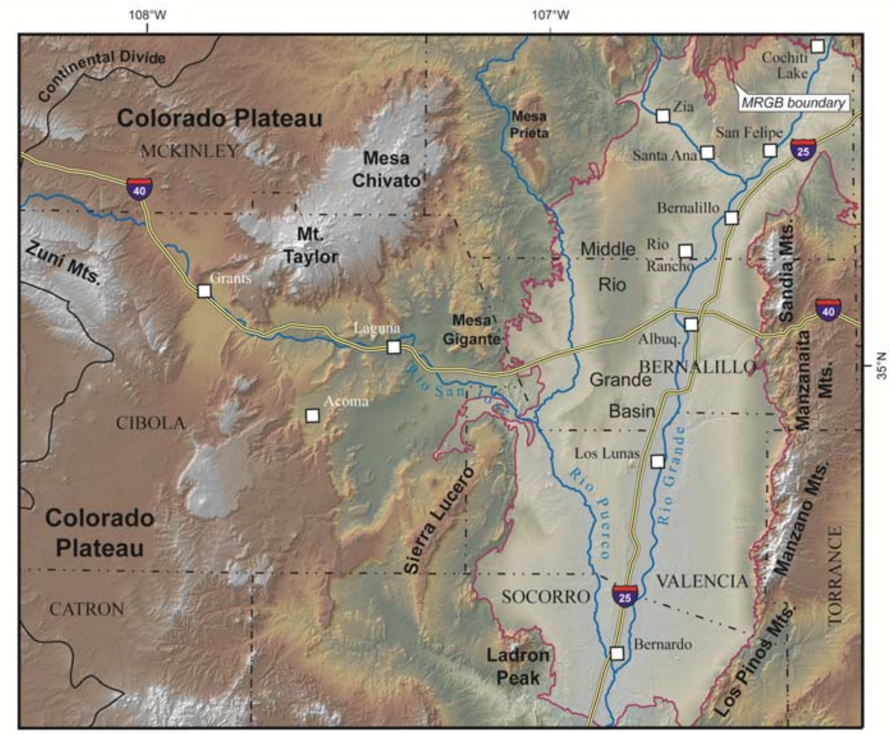

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ABSTRACT

Recent interest in the availability of deep groundwater resources along the structurally complicated transition between the Colorado Plateau and the Rio Grande rift in north-central New Mexico, resulted in the development of groundwater-flow models that suggested an impact on the Middle Rio Grande Basin (MRGB, also known as the Albuquerque Basin) from long-term pumping of wells that would exploit pre-Cenozoic aquifer units (Melis, 2009). Refinement of the regional conceptual geologic framework of the Colorado Plateau-MRGB transition was done in order to aid in the development of a revised groundwater-flow model of this region by Melis et al. (2011). The refined geologic framework was based on a compilation of previous stratigraphic work, an examination of data from 72 deep wells, and modifications to structure-contour maps of the base of the Upper Cretaceous Dakota Formation (Thaden and Zech, 1984) and the top of Proterozoic basement (Broadhead et al., 2009). The internal structure of the MRGB is dominated by subbasins and buried structural culminations that likely influence flows of deep groundwater. Structural control on the distribution of springs along the western flank of the MRGB is suggested by variations in basin-margin structure and stratal dips. Few springs are found along the highly faulted Laguna bench, whereas springs are common along the faulted eastern front of the Lucero uplift, where strata dip away from the MRGB boundary. Groundwater-flow across faults was examined by projecting juxtaposition seals and conduits across three fault zones that locally define the northwestern structural margin of the MRGB. A preliminary result of the fault juxtaposition analyses suggest discontinuous and discrete windows of groundwater flow along portions of basin-margin faults.

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INTRODUCTION

This report provides geologic information to develop a conceptual geologic framework that was incorporated into a numerical model of groundwater flow along the transition between the Colorado Plateau and Middle Rio Grande Basin (Melis et al., 2011). This report summarizes compositional and stratigraphic thickness data from previous studies, and interprets stratigraphic data using subsurface information from 72 deep wells in the southeastern Colorado Plateau and Middle Rio Grande Basin (MRGB, also known as the Albuquerque Basin). A conceptual geologic framework of the northwestern flank of the MRGB was developed by extending a series of available geologic cross sections west onto the Colorado Plateau (Russell and Snelson, 1994; Maldonado et al., 2007; and Connell, 2008b; Melis, 2009; and Grauch and Connell, *in press*). Structure-contour maps were refined for important stratigraphic surfaces. Broadhead et al. (2009) produced a structure-contour map of the top of Precambrian that provides a lower bounding surface for the entire Phanerozoic sedimentary succession. A large part of the structure-contour map of the base of the Upper Cretaceous Dakota Formation by Thaden and Zech (1984) was digitized and re-interpreted along the eastern flank of the Colorado Plateau and MRGB. In order to better understand the flow of groundwater into the MRGB, conduit-seal distributions were examined along three basin-border fault zones on the northwestern flank of the MRGB.

Interest in exploiting deep (more than 2500 ft below ground surface) groundwater sources for communities in the MRGB was prompted after two exploratory wells were drilled in the Rio Puerco Valley in 2007 to examine the feasibility of appropriating deep groundwater in upper Paleozoic strata (Intera, 2008). In order to evaluate the possible effects of long-term groundwater appropriation along the transition between the MRGB and Colorado Plateau (Fig. 1), John Shomaker and Associates, Inc. (JSAI) completed a groundwater-flow model for the New Mexico Interstate Stream Commission (Melis, 2009). The JSAI groundwater-flow model expanded on an earlier regional, multi-layer, finite difference groundwater-flow model (MODLFOW) developed by the U.S. Geological Survey (USGS) for the MRGB (McAda and Barroll, 2002). A principal objective of the JSAI groundwater-flow model was to evaluate the effects of deep groundwater withdrawals on the MRGB aquifer system after long-term pumping of groundwater from pre-Cenozoic aquifer units along Colorado Plateau-MRGB transition. Preliminary results of the JSAI groundwater-flow model suggested that long-term, deep groundwater appropriation of 202,000 acre-ft/yr could affect the MRGB and Rio Grande (Melis, 2009).

The MRGB groundwater-flow model of McAda and Barroll (2002) used a conceptual hydrogeologic framework of the MRGB (developed in the 1990s) that focused primarily on Cenozoic stratigraphy and structure (e.g., Bartolino and Cole, 2002). In their flow model, details of the Mesozoic and Paleozoic geology and structure were highly generalized and largely neglected. The transition between the southeastern Colorado Plateau and the northwestern flank of the MRGB contains a complicated zone of faults (Slack and Campbell, 1976; and Callender and Zilinski, 1976) that could influence the flow of groundwater to the MRGB. Refinements to the geologic framework of this complicated structural transition could resolve questions about the potential hydrologic impact of long-term development of Paleozoic and Mesozoic aquifer zones.

A conceptual geologic framework was developed herein and incorporated into a revised groundwater-flow model by Melis et al. (2011). This geologic framework was developed through a compilation of regional surface and subsurface geologic mapping, and stratigraphic interpretations of available wells in the region. Regionally extensive geologic units, such as the Upper Cretaceous Dakota Formation (Rocky Mountain Association of Geologists, 1972; and Grant and Foster, 1989) and the base of the Phanerozoic sedimentary succession (Foster and Stipp, 1961; and Broadhead et al., 2009) were used to refine the depths of potential aquifer targets and to define model layers and estimate fault displacements.

Hydrogeologic connections between the deeper pre-Cenozoic aquifers and the MRGB are difficult to document because of the generally great depth of these units beneath the synrift Santa Fe Group basin-fill, which comprises the regional aquifer system of the MRGB (e.g., Connell, 2004). Although many parts of the Colorado Plateau have been extensively surveyed for petroleum resources, few wells have been drilled in the transition to the MRGB. Recent interest in basin-centered gas exploration and coal-bed methane (Johnson et al., 2001) has prompted the recent exploratory drilling in the region, and additional data may become available. Well data was collected and stratigraphic picks were interpreted and compiled from borehole data. Potential influences of deep groundwater appropriation in the Colorado Plateau-MRGB transition on the Rio Grande should be related to the hydrologic character of the basin-bounding faults which can act as impediments to fluid flow (Knipe, 1993, 1997; Caine, 1996; Rawling et al., 2001; and Doughty, 2003). Improved characterization of faults and stratigraphic units across the Colorado Plateau-MRGB transition can reveal hydrogeologic connections between deep-seated aquifer zones and the Santa Fe Group.

Study area

The study area occupies the model domain of the revised JSAI groundwater-flow model (Melis et al., 2011) and includes 11,384 mi^2 (29,486 km^2) of north-central New Mexico (Fig. 1); the MRGB includes about a quarter of the study area. The study area contains a wide variety of sedimentary and volcanic rocks of late Paleozoic through Holocene age (Fig. 2) that encompasses parts of the southeastern Colorado Plateau, Zuni Mountains, San Juan Basin, southern flanks of the Sierra Nacimiento and Jemez Mountains, Lucero uplift, and the MRGB from Cochiti Lake to San Acacia (Thorn et al., 1993).

Previous work

This study relied on many earlier investigations of the geology of the Colorado Plateau and basins of the Rio Grande rift (Fig. 2). Much of this stratigraphic data has been compiled from earlier regional studies (Kelley, 1977; Thaden and Zech, 1984; Molenaar and Baird, 1992; Baldwin and Anderholm, 1992; NMBGMR, 2003; Maldonado et al., 2007; Williams and Cole, 2007; Connell, 2008b; and Grauch and Connell, *in press*). The geology of the study area was mapped at a scale of 1:500,000 by the U.S. Geological Survey (Thaden and Zech, 1984; and NMBMGR, 2003). The Albuquerque Basin (including the MRGB) was mapped by Kelley (1977) at a scale of 1:190,000, and parts of the Colorado Plateau-MRGB transition were mapped by the U.S. Geological Survey at a scale of 1:100,000 (Dillinger, 1990; and Williams and Cole, 2007). The central and northern parts of the MRGB were mapped by the New Mexico Bureau of Geology and Mineral Resources and U.S. Geological Survey (Connell, 2006, 2008b; Minor, 2006; and Maldonado et al., 2007).

The geologic structure and stratigraphy of central New Mexico has been treated by numerous workers. Results of many studies have been described in various guidebooks and special publications by the New Mexico Geological Society (Siemers, 1974; Woodward and Northrop, 1976; Fassett, 1977; Wells and Lambert, 1981; Grambling and Wells, 1982; Anderson et al., 1989; Chamberlin et al., 1994; Pazzaglia and Lucas, 1999; Mack and Giles, 2004; symposia published by the New Mexico Museum of Natural History and Science. (Lucas and

Zeigler, 2004; and Lucas et al., 2005), and theses conducted by students at the University of New Mexico and New Mexico Institute of Mining and Technology (Mirsky, 1955; Campbell, 1967; Slack, 1973; Picha, 1982; Little, 1987; Lozinsky, 1988; and Menne, 1989).

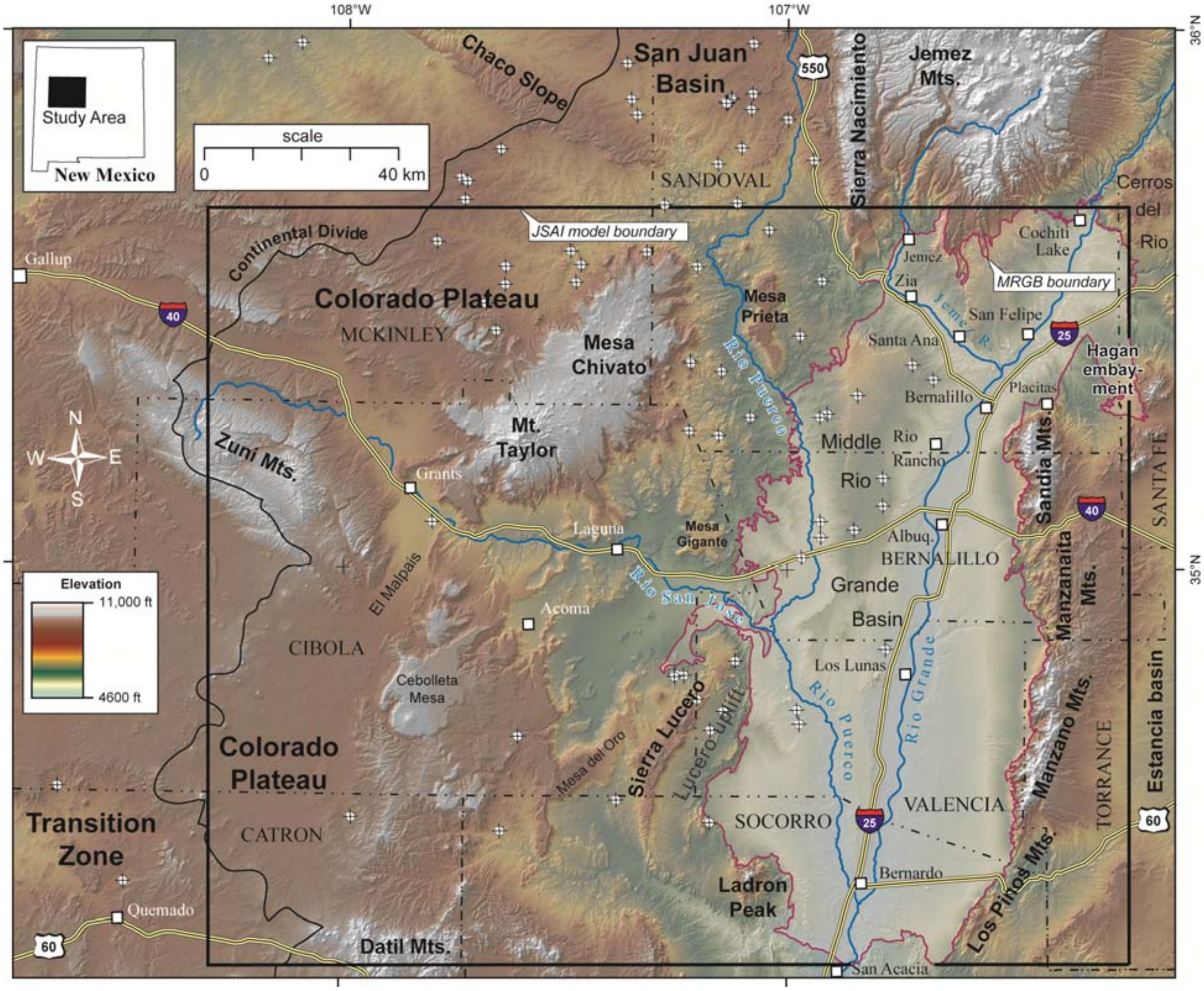

Figure 1. Study area location (box), illustrating major physiographic features, boundary of the MRGB (red line), and wells examined in this report.

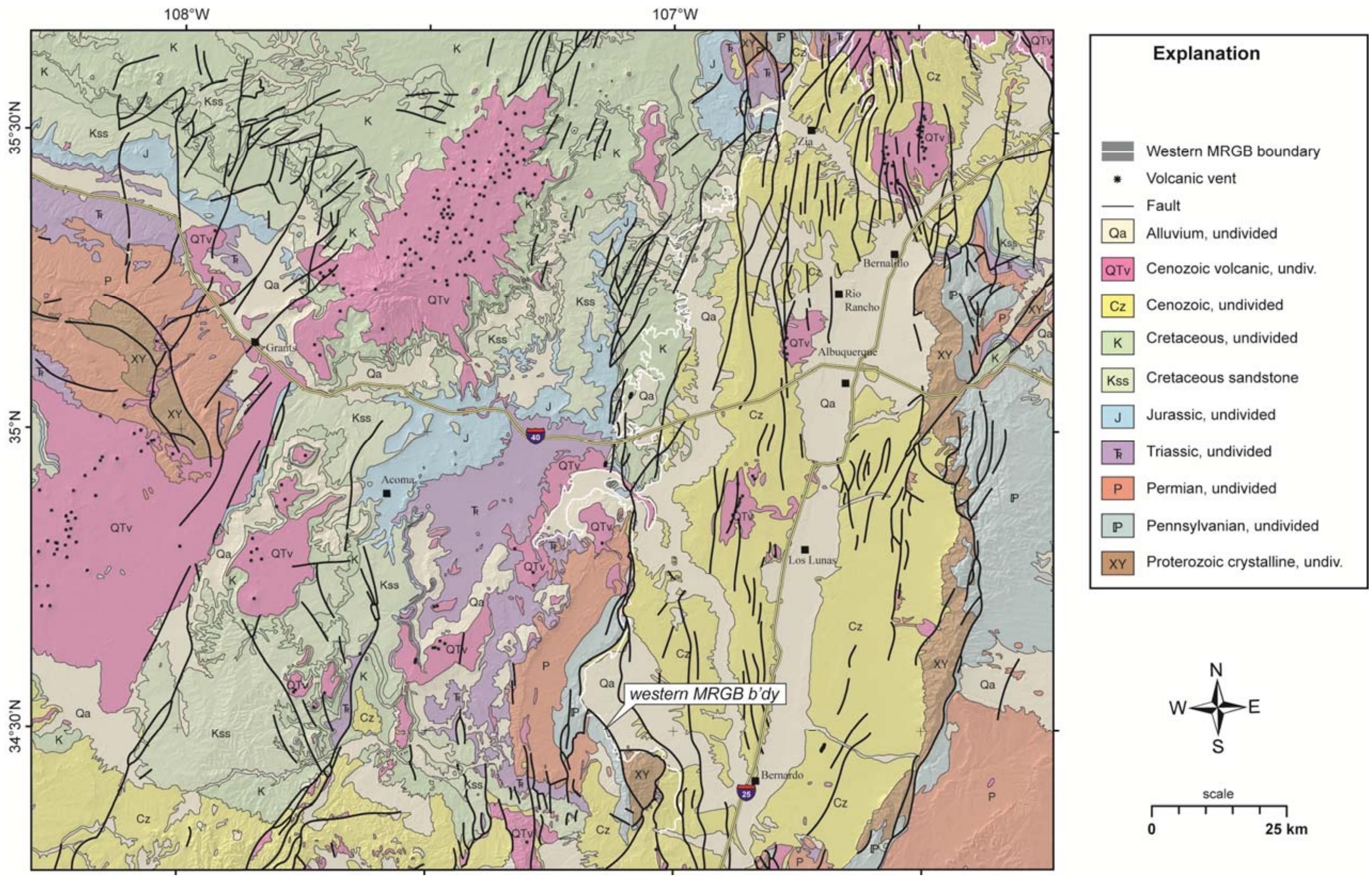

Figure 2. Geologic map of study area (generalized from NMBGMR, 2003) and the western boundary of the MRGB.

The stratigraphy of the study area has been extensively studied and is summarized below. Early work on the upper Paleozoic succession was completed by Kelley and Wood (1946), Wengerd and Matheny (1958), and Baars (1962, 1982). Stratigraphic correlations across the Rio Grande rift have been made by Lucas et al. (1999b, c). Regional stratigraphic surfaces have been mapped across New Mexico and the Rocky Mountains in atlas compilations by the Rocky Mountain Association of Geologists (1972) and Grant and Foster (1989). Important stratigraphic localities include the northern flank of the Sandia Mountains and adjacent Hagen embayment (Picha, 1982; and Menne, 1989; Lucas and Heckert, 1995; and Lucas et al., 1999a); Sierra Lucero and the Lucero uplift (Kelley and Wood, 1946; Mirsky, 1955; Little, 1987; Lucas and Heckert, 1994, 1995 & 2004; Krainer and Lucas, 2004a, b; Lucas and Krainer, 2004, 2009; and Zeigler and Lucas, 2005); Zuni Mountains (Baldwin and Anderholm, 1992); Sierra Nacimiento (Woodward, 1987); Colorado Plateau and San Juan Basin (Stone et al., 1983; Molenaar, 1983a, b, 1988; Fassett, 2000; and Smith and Lucas, 1991), and Albuquerque Basin (e.g., Galusha, 1966; Hawley, 1978; Gorham and Ingersoll, 1979; Gawne, 1981; Kautz et al., 1981; Osburn and Chapin, 1983; Erskine and Smith, 1993; Lozinsky and Tedford, 1991; Connell et al., 1998, 1999 and 2005; Lucas et al., 1997; Tedford and Barghoorn, 1999; and Connell, 2004, 2008a).

Summaries of the petroleum potential for the Albuquerque Basin (MRGB) and Colorado Plateau (exclusive of the San Juan Basin) have been made by staff of the U.S. Geological Survey (e.g., Molenaar, 1988; and Johnson et al., 2001) and industry geologists (e.g., Black, 1982). Regional stratigraphic correlations based on well data have been summarized by previous workers (Foster and Stipp, 1961; Reese, 1971 and 1978; Foster, 1978; Black and Hiss, 1974; Black, 1982; Broadhead and Black, 1989; Molenaar and Baird, 1992; Lozinsky, 1994; Maldonado et al., 1999 and 2007; Connell, 2006; and Sawyer and Minor, 2006).

Hydrogeologic investigations in the study area include studies of the San Andres-Glorieta aquifer (Summers and Kottlowski, 1969; and Baldwin and Anderholm, 1992); Jemez River and northwestern Albuquerque Basin (Craigg, 1992); Colorado Plateau and San Juan Basin (Risser and Lyford, 1983; Stone et al., 1983; Craigg et al., 1989 and 1990; Kernodle et al., 1989, 1990; Dam et al., 1990a, b; Levings et al., 1990a, b; and Thorn et al., 1990a, b); and the MRGB (Titus, 1963; Hawley et al., 1995; Thorn et al., 1993; McAda and Barroll, 2002; Sanford et al., 2004; and Plummer et al., 2004). Hydrogeologic characteristics of the stratigraphy exposed along the northern flank of the Sandia Mountains were also examined in detail by Johnson et al. (2002).

METHODS

The stratigraphy of the study area was compiled using available geologic maps, stratigraphic investigations, and well data. A database of petroleum wells in New Mexico is maintained at the GOTECH website at the New Mexico Institute of Mining and Technology (http://octane.nmt.edu/gotech). According to this online database (accessed in 2010), approximately 820 petroleum wells have been drilled in the study area. Of these wells, few have been drilled along the transition between the Colorado Plateau and MRGB (Fig. 3). The data (and quality) available for the GOTECH database are variable, ranging from location information only, to detailed logs of the geology and borehole geophysical logs.

Additional well data was accessed through the New Mexico Bureau of Geology Subsurface Library (Broadhead and Scholle, 2009), and the State of New Mexico Oil Conservation Division (http://ocdimage.emnrd.state.nm.us, website accessed multiple times in 2010-2011). Well data are also available through the U.S. Geological Survey Petroleum Information Center in Denver, Colorado (David A. Sawyer, 2010, personal communication), and compilations by Engler et al. (2001) and Broadhead et al. (2009). The New Mexico Office of the State Engineer maintains a database of water-supply wells for the state (http://www.ose.state.nm.us, accessed in 2010) that shows 22,522 wells reported within the study area. These wells were not examined because they typically target shallow ground-water resources, and the geologic data for many of these wells is typically incomplete.

Oil and gas wells were used for estimating stratigraphic thickness because they commonly contain geologic data and borehole geophysical logs that can be used to pick stratigraphic boundaries and units. Stratigraphic picks from 72 wells were derived from reports on the wells and scout tickets and completion reports. Where available, borehole geophysical logs were examined to verify stratigraphic boundaries and correlate borehole geophysical log data (commonly using electrical-resistivity and gamma-ray logs). Well location and completion data and well-depth picks are given in the Appendix. Most of the study area lies south of the extensively studied San Juan Basin and few deep wells have been drilled along the transition between the Colorado Plateau and MRGB (Fig. 3).

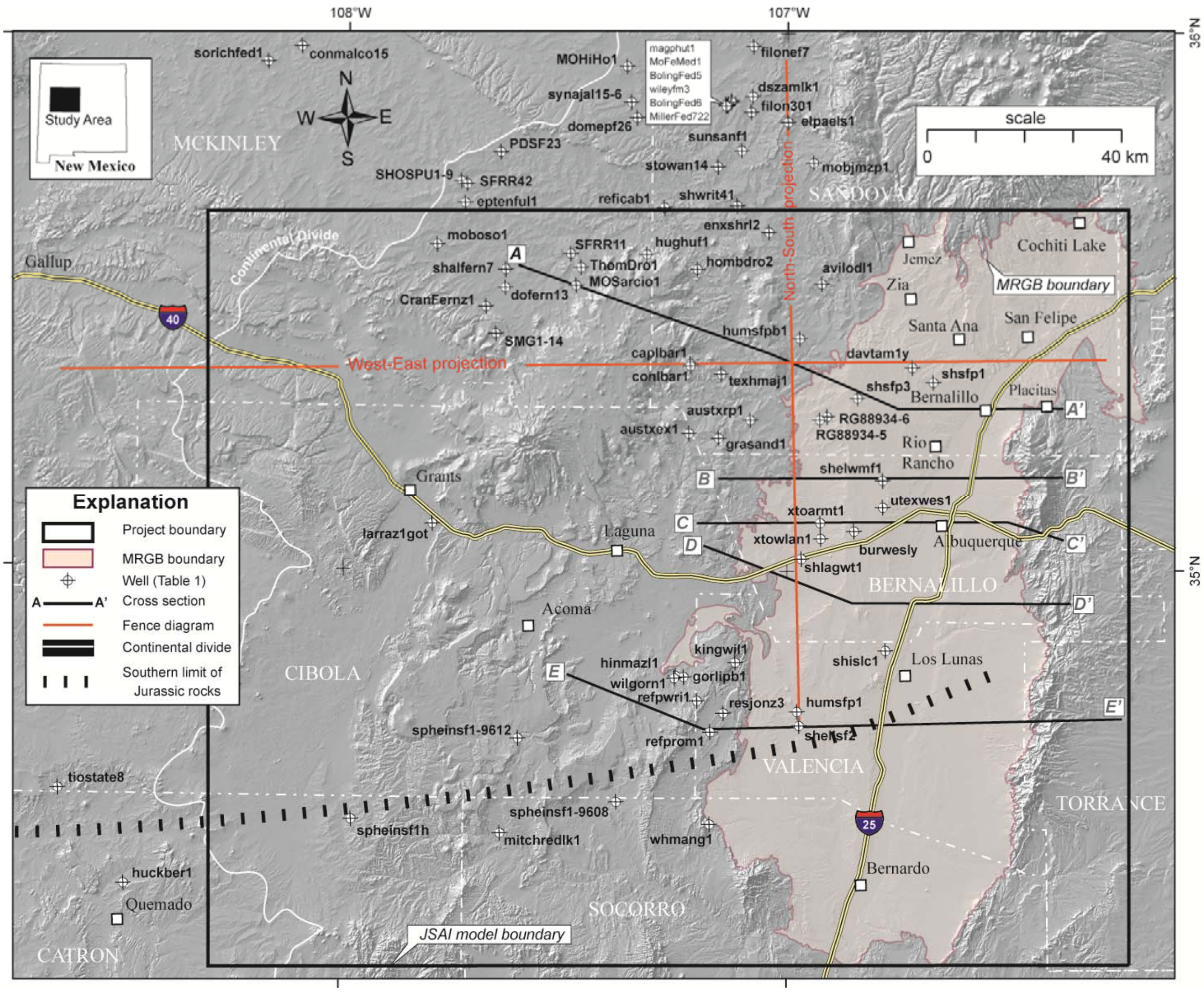

Figure 3. Shaded-relief map of study area and vicinity, showing locations and names of wells examined in this study (Appendix), the southern limit of Jurassic rocks (Grant and Foster, 1989), and locations of cross sections (Plate 2) and projected well fences (Figs. 7 and 8).

The regional geology was generalized from the State Geologic Map of New Mexico (Fig. 2). A map of faults and folds comes from a structure-contour map of the base of the Upper Cretaceous Dakota Formation (Thaden and Zech, 1984). Although the structure-contour map of the Dakota Formation was completed at a scale of 1:500,000 using metric units of elevation, it is very detailed and portrays faults that were compiled from numerous detailed studies. In my opinion, the map by Thaden and Zech (1984) provides the most detailed and comprehensive regional compilation of geologic structures available in the study area. Structural refinements to the Thaden and Zech (1984) map were made by interpreting geologic data from maps of the Grants sheet (1:100,000, Dillinger, 1990), Albuquerque sheet (scale 1:100,000, Williams and

Cole, 2007), Isleta Reservation and vicinity (scale 1:50,000, Maldonado et al., 2007), Albuquerque-Rio Rancho metropolitan area (scale 1:50,000, Connell, 2006 and 2008b), and a preliminary geologic map of the Jemez Mountains (David A. Sawyer, 2010, personal communication).

GEOLOGIC SETTING

The study area lies within the junctions of the southern Rocky Mountains, southeastern Colorado Plateau, and Rio Grande rift. This study focuses on the geologic characteristics of the transition between the Colorado Plateau and MRGB (part of the Rio Grande rift).

Colorado Plateau

The Colorado Plateau in New Mexico is characterized by erosional landscapes that have been carved on weakly deformed sedimentary and volcanic rocks (Figs. 1 & 2). The resulting landscapes are characterized by broad tablelands, some capped by basaltic rocks, and deep valleys (Hawley and Love, 1981; and Love, 2002). Much of the southeastern flank of the Colorado Plateau lies within the Acoma-Zuni and Navajo sections. The Navajo section lies between the Chuska Mountains, along the Arizona-New Mexico border, and Sierra Nacimiento, and includes the San Juan Basin. The Acoma-Zuni section extends south from the Chaco slope of the southern San Juan Basin to the Transition Zone and Datil Mountains at the southern margin of the study area. The Acoma-Zuni section contains the basement cored Zuni Mountain uplift and the Lucero uplift. The Zuni uplift is flanked by cuestas of Pennsylvanian and Permian limestone and Triassic and Jurassic sandstone beds. The Lucero uplift forms a west-dipping succession of upper Paleozoic sandstone, shale, and limestone, containing numerous springs and travertine accumulations near western structural boundary of the MRGB (Callender and Zilinski, 1976). These uplifts are the result of Laramide compressional tectonics (Cather, 2004). The southwestern part of the study includes the Acoma Sag and Zuni embayment, containing thick accumulations of upper Paleozoic strata (Wengerd and Matheny, 1958; and Kues and Giles, 2004).

Mount Taylor (elevation: 11,301 ft, 3445 m) is a Pliocene composite-type statovolcano that is surrounded by broad basaltic-lava-capped mesas; the most prominent are Mesa Chivato and Mesa Prieta (Fig. 1). Extensive Plio-Pleistocene volcanic flows and vents are also present along the flanks of the Zuni Mountains, Mount Taylor, and the northern Lucero uplift (Baldridge et al., 1987; Mabery, 1997; Hallett et al., 1997; and Baldridge, 2004). The San Juan Basin is an asymmetrical basin containing a thick sequence of Mesozoic and Paleogene sedimentary rocks that were deposited in shallow marine and terrestrial environments (e.g., Cather, 2004). Phanerozoic rocks in the southeastern park of the San Juan Basin are estimated to be between 4,000 and 11,000 ft (1.2-3.4 km) in maximum thickness (e.g., Sawyer and Minor, 2006). The southern part of the San Juan Basin lies within the study area.

The southeastern flank of the Colorado Plateau contains the Rio Puerco and Rio San Jose drainage systems, which comprise one of the largest tributaries to the Rio Grande in New Mexico. The Rio Puerco drains nearly 19,000 km^2 east of the Continental Divide, the western flank of the Sierra Nacimiento, and crosses the western MRGB before joining the Rio Grande near Bernardo, New Mexico (Love and Connell, 2005). The headwaters of the Rio Puerco are at elevations of more than 3000 m in the Sierra Nacimiento, on Mount Taylor, and in the Zuni Mountains. Nearly 3300 km^2 of the Rio Puerco drainage is covered with lava flows that typically resist erosion and preserve former levels of streams and valley margins. The Rio San Jose drains approximately 9500 km^2 of the Colorado Plateau from the Continental Divide and Zuni Mountains eastward to the Rio Puerco in the Albuquerque Basin (MRGB). The smaller Jemez River heads in Pleistocene volcanic rocks of the Jemez Mountains and eastern flank of the Sierra Nacimiento. The Jemez River flows across upper Paleozoic strata where it enters the northern flank of the MRGB near Jemez Pueblo, and flows across Cenozoic volcanic and sedimentary rocks of the Santa Fe Group, where it joins the Rio Grande near Bernalillo, New Mexico (Craigg, 1992).

The Rio Puerco fault zone lies between the northern end of the Lucero uplift and the southern tip of the Sierra Nacimiento (Fig. 1). This zone contains a complicated array of faults that cut mostly Cretaceous age strata and forms part of the structural transition between the Colorado Plateau and MRGB (Dane, 1936; Slack, 1973, 1975; and Slack and Campbell, 1976). The Rio Puerco fault zone contains numerous *en echelon* normal faults that have an overall southeast-down sense of displacement and were interpreted to have been active during Paleogene time (Slack and Campbell, 1976).

Faults related to later (mostly Neogene) extension of the Rio Grande rift and development of the MRGB lie just east of (and overlap with) the Rio Puerco fault zone. Rift-age faults cut Neogene strata and have generally more northerly strikes. Some of these faults may have originated during Paleogene time and were reactivated during the Neogene (Slack and Campbell, 1976). The Moquino and Sand Hill faults may reflect both Paleogene and Neogene displacement histories (Connell, 2008b; and Sengebush, 2008).

Rio Grande rift

The Rio Grande rift is a series of axially aligned extensional basins that developed within a much broader zone of Cenozoic deformation in the Basin and Range province of western North America. The Rio Grande rift in northern New Mexico consists of oppositely-tilted half-graben basins that are separated by zones of strain accommodation. Many of these half-graben basins are flanked by basement-cored uplifts, such as Ladron Peak and the Sandia, Manzanita, Manzano, and Los Pinos Mountains. The MRGB is a large structural basin in the Rio Grande rift, and represents a transitional tectonic feature between the topographically and structurally well-defined northern Rio Grande of northern New Mexico and southern Colorado, and the broader Basin and Range and Rio Grande rift provinces to the south (Kelley, 1982; Chapin and Cather, 1994; and Connell, 2004). The MRGB is about 160 km long and faulted on all sides (Fig. 2); the maximum width is about 55 km, narrowing to approximately 12 km to the south. The western flank of the study area forms a shallowly buried structural bench (Laguna bench of Russell and Snelson, 1994) that is defined by the traces of the San Ysidro, and Cat Mesa fault zones and western basin-border faults. Late Paleozoic (ancestral Rocky Mountain), Cretaceous-Paleogene (Laramide, *ca.* 80-40 Ma), and Rio Grande rift tectonic events influence the spatial distribution of deposits and faults in the study area (Kelley, 1982; and Pazzaglia et al., 1999).

The MRGB has been segmented into structural subbasins and re-entrants (embayments) that are recognized in regional gravity, deep oil-test, and seismic reflection data (Russell and Snelson, 1994; and Grauch et al., 1999). From north to south, these are the Santo Domingo, Calabacillas, and Belen subbasins. Subbasin boundaries are defined by broad, generally discontinuous zones of high gravity-anomaly values that are interpreted as intrabasinal structural culminations (Hawley, 1996; Maldonado et al., 1999; and Grauch and Connell, *in press*). The Calabacillas and Santo Domingo subbasins are dominantly east-tilted and the Belen subbasin is a complexly faulted graben with prominent axial folds or horsts (Grauch and Connell, *in press*). The southern Belen subbasin narrows towards the Socorro Basin near San Acacia, New Mexico. Subbasin boundaries are not universally accepted and are difficult to determine, but are thought to influence the distribution of facies in the basin (Cole et al., 1999). The lack of strong structural and topographic expression of these subbasin boundaries suggests that these northwest-trending structures may represent older boundaries that have been concealed by younger basin fill (Maldonado et al., 1999).

The sedimentary basin fill and interbedded volcanic deposits of Rio Grande rift basins are collectively known as the Santa Fe Group (Spiegel and Baldwin, 1963; and Cather and Chapin, 1994), and comprise the regional aquifer system of the MRGB (Bartolino and Cole, 2002). Regionally, these strata accumulated between the late Oligocene and early Pleistocene (Kelley, 1977; Hawley, 1978; Gile et al., 1981; Chapin and Cather, 1994; and Connell, 2004). Deposition of the Santa Fe Group ceased as a result of regional incision that led to the formation of the present valleys (Spiegel and Baldwin, 1963). The Santa Fe Group is generally less than one kilometer thick along the western margin of the MRGB. Oil-well data indicate that the basin contains as much as 14,435 ft (4.4 km) of synrift basin fill (Lozinsky, 1994). The deepest portions of the MRGB have not been completely penetrated by wells, so the basin fill could exceed 16,400 ft (5 km) in thickness (Grauch and Connell, *in press*).

STRATIGRAPHY

North-central New Mexico contains a nearly complete succession of Mississippian through Holocene sedimentary and igneous rocks that overlie a regional nonconformity with Proterozoic crystalline basement (Pazzaglia et al., 1999). Regional trends in stratigraphic thickness were estimated by examining stratigraphic units exposed in the Colorado Plateau, southern Sierra Nacimiento, Lucero uplift, Sandia Mountains, and the Hagan embayment. Stratigraphic picks from the well data are summarized in the Appendix.

Reported values of stratigraphic thickness were taken from published field-based studies and graduate thesis projects, where thickness has been adjusted for bedding inclination, and thus, represent actual measurements of deposit thickness. Limitations to field-based measurements of stratigraphic thickness occur where faults are not recognized or beds are miscorrelated. Thickness values determined from boreholes have not been adjusted for stratal tilting, which would increase the apparent thickness of stratigraphic units. Much of the Colorado Plateau exposes gently dipping strata, so thickness errors caused by inclined bedding should be relatively small. Faults that cross boreholes can also alter apparent deposit thickness. For example, normal faulting will decrease thickness, whereas, reverse faulting increases thickness.

Major rock units recognized in the study area include (but are not limited to) the Sandia Formation, Madera Group (Gray Mesa & Atrasado Fms), Abo and Yeso Formations, Glorieta Sandstone and San Andres Limestone, Chinle Group, Agua Sarca (Zarca) Formation, Entrada Sandstone (Formation), Todilto Formation, Morrison Formation, Dakota Sandstone (Formation), Mancos Shale, Gallup Sandstone (Member), Point Lookout Sandstone, Mesaverde Group, Menefee Formation, and Lewis Shale (Figs. 4 and 5). Members of the Morrison Formation and other units in the Cretaceous section are recognized, but have not been included in the appendix data. Important markers that were included in many well logs, include the Entrada Sandstone, Todilto Formation, Morrison Formation, and Dakota Formation (Fig. 6). Figure 4 is a generalized stratigraphic column of the sedimentary rocks found in the study area. For this study, undivided Pennsylvanian strata are included in the Madera Group. Figure 5 portrays the stratigraphy of the Cretaceous section in the San Juan Basin. The Hosta and Dalton Sandstones (Fig. 5) are locally recognized in the well data and shown on Figures 7 and 8. Thickness data presented on this figure are from stratigraphic studies summarized below and correlations of well data (Appendix).

Proterozoic

Proterozoic igneous and metamorphic rocks form the basement of central New Mexico. These rocks contain older (Paleoproterozoic) metamorphosed sedimentary (mostly schist and quartzite) and volcanic rocks that were intruded by younger (Mesoproterozoic) granitic plutons. Basement rocks are commonly exposed in the cores of rift-flanking uplifts of the Sandia, Manzanita, Manzano, and Los Pinos Mountains, and Ladron Peak. Proterozoic rocks are also exposed in the cores of Laramide uplifts in the Zuni Mountains, Sierra Nacimiento, and Sierra Lucero. A small inlier of Proterozoic rock is exposed along the western front of the Lucero uplift (Plate 1).

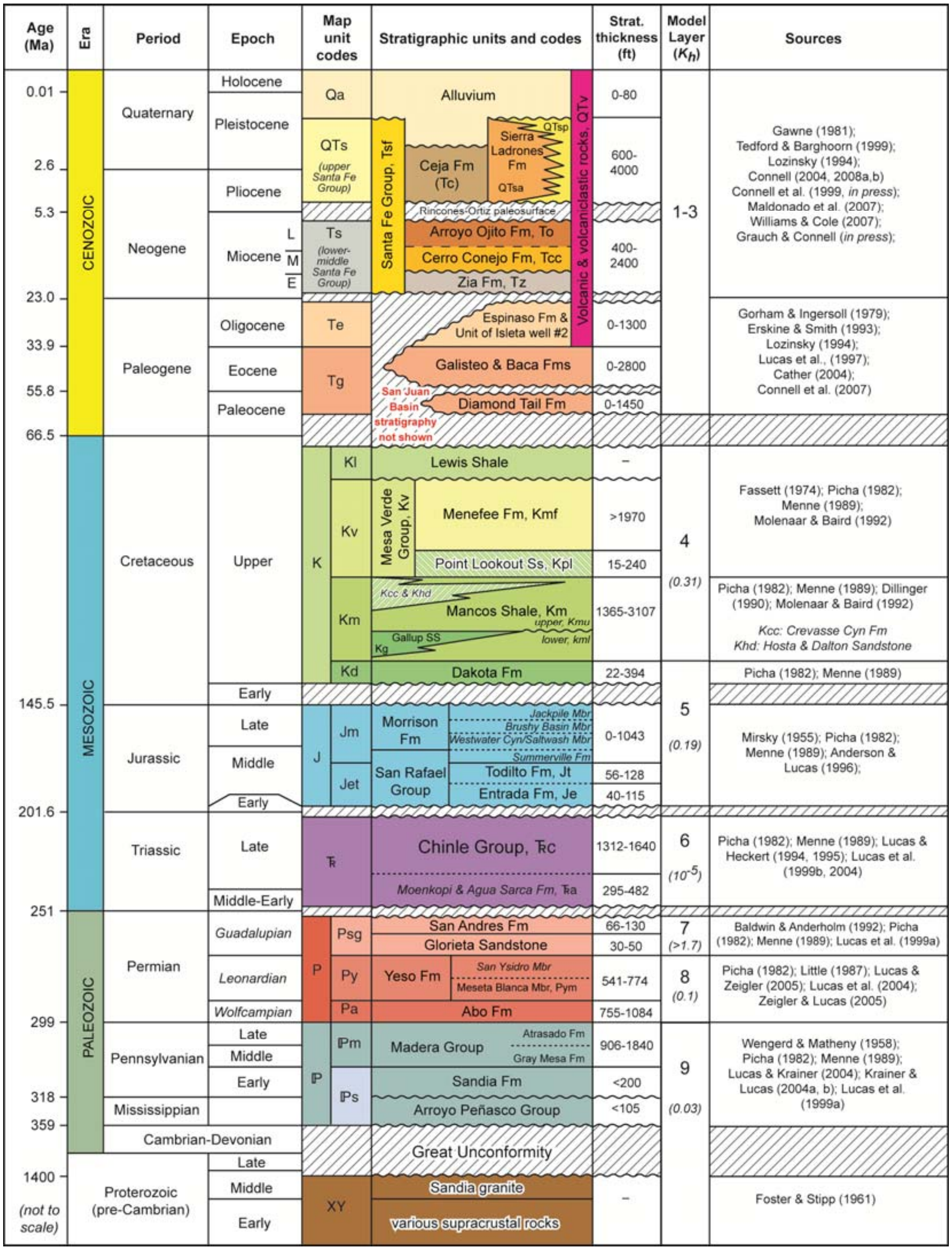

Figure 4. Stratigraphic column of major geologic units in study area and estimated thickness based on regional stratigraphic studies. Hachured lies denote stratigraphic lacunae and wavy lines indicate major unconformities. Groundwater-flow model layers and horizontal hydraulic conductivity values (K_h, ft/day) from Melis et al. (2011). Model layers 1-3, 5, and 7 are considered conduits; the remaining layers are seals.

Paleozoic

Scattered Mississippian and Pennsylvanian sedimentary rocks nonconformably overlie Proterozoic crystalline basement rocks (Fig. 4). Pre-Mississippian rocks have been removed by erosion and are not present in the study area region. The upper Paleozoic/Proterozoic contact is locally marked by granitic sediment commonly labeled as “granite wash” in well logs. Mississippian strata form relatively thin (<105 ft, < 32 m) units of limited exposure and discontinuous lateral extent. Mississippian strata mostly belong to the Arroyo Peñasco Group, which contains well-cemented sandstone, limestone, and shale.

The Pennsylvanian Sandia Formation disconformably overlies Mississippian rocks or it nonconformably overlies Proterozoic basement. The Sandia Formation contains interbedded well-cemented, olive-brown to gray, sandstone and limestone. The Sandia Formation grades upsection into marine rocks of the Madera Group. The Sandia Formation is generally less than 200 ft (61 m) thick. For the purposes of this study, the “granite wash” (reported in wells), Mississippian, and basal siliciclastic rocks of Pennsylvanian succession are grouped into the Sandia Formation. In the wells interpreted in this study (Appendix), the thickness of the Sandia Formation ranges from about 95-194 ft (29-59 m) with an average thickness of about 151 ft (46 m).

The middle and upper Pennsylvanian Madera Group is commonly subdivided into marine rocks of the lower Gray Mesa Formation and the upper Atrasado Formation (e.g., Kues and Giles, 2004). The Gray Mesa Formation contains thick, massive, gray limestone beds. The overlying Atrasado Formation is a lithologically variable succession of interbedded gray to olive-gray limestone and shale, and tan to reddish-brown arkosic sandstone. The upper boundary with the Abo Formation is gradational, and is locally defined by the presence of Bursum Formation limestone (not shown on Fig. 4; Lucas and Krainer, 2004, 2009). The stratigraphic thickness of the Madera Group is about 1247-1542 ft. In the wells interpreted in this study (Appendix), the combined thickness of Madera rocks range from about 906-1840 ft (276-561 m) with an average thickness of about 1220 ft (372 m).

Permian strata are divided into four regionally mappable units (listed in ascending stratigraphic order): Abo, Yeso, Glorieta (Sandstone), and San Andres (Limestone) Formations. The Lower Permian Abo Formation is succession of fluviatile sediments that ranges from about 755-1083 ft (230-330 m) in thickness and consists of predominantly reddish-brown to orange-brown mudstone with subordinate sandstone, with the proportion of sandstone increasing upsection. The thickness of the Abo Formation in wells (Appendix) ranges from about 745-1184 ft (227-361 m), with an average thickness of about 951 ft (290 m). The Lower Permian Yeso Formation (nonmarine) consists of 541-689 ft (165-210 m) of fine-grained orange-brown sandstone and siltstone that conformably overlies strata of the Abo Formation. The Yeso Formation contains two members in the study area. The Meseta Blanca Member is a light-orange to light-gray, medium- to coarse-grained sandstone that forms the lower ~115 ft (~35 m) of the Yeso Formation. The overlying San Ysidro Member consists of orange-brown laminated sandstone and interbedded siltstone, sandstone, and gypsum. In the wells interpreted in this study (Appendix), the thickness of the Yeso Formation ranges from about 640-774 ft (195-236 m), with an average thickness of about 656 ft (200 m).

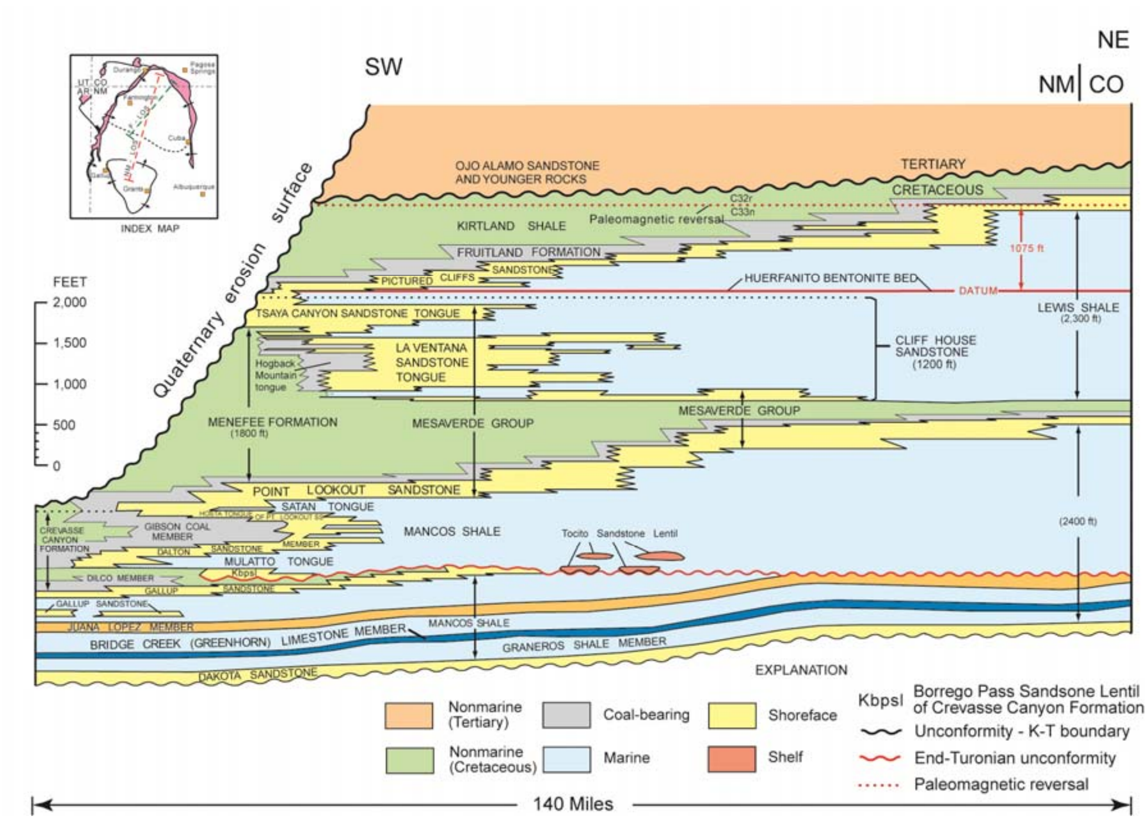

Figure 5. Index map and stratigraphic diagram illustrating Cretaceous units in the San Juan Basin in the northwestern part of the study area (from Fassett, 2000).

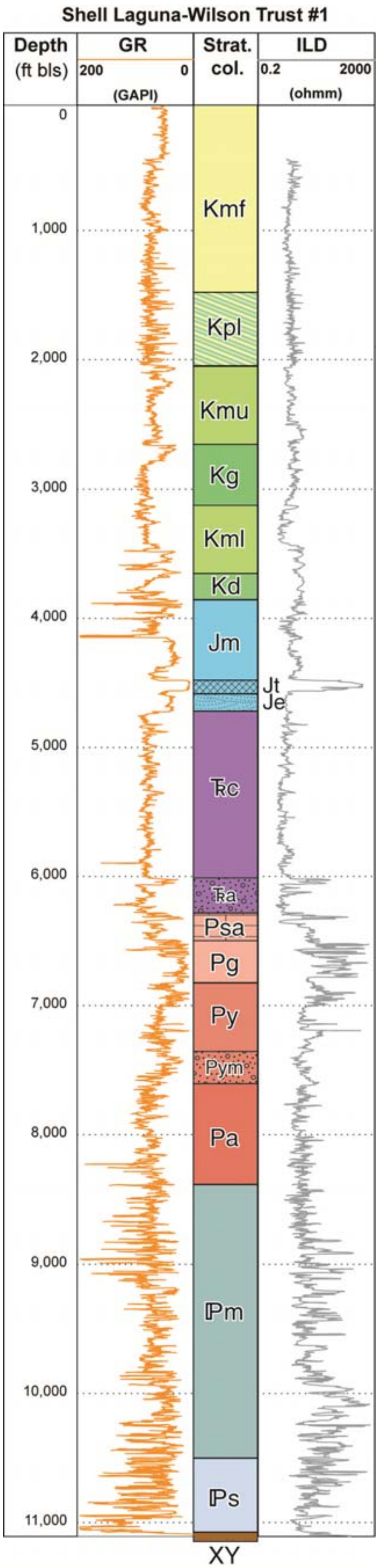

Figure 6. Stratigraphic interpretation of borehole geophysical logs for the Shell Laguna-Wilson Trust well (*shlagwt1*, Appendix); depth in feet below land surface (bls). Well logs include gamma ray (GR) and deep induction resistivity (ILD) that were digitized from paper logs (digital data courtesy of David A. Sawyer). See Figure 4 for unit abbreviations.

The Upper Permian Glorieta Sandstone (Formation) disconformably overlies the Yeso Formation, except near the Zuni uplift, where the contact is conformable (Baldwin and Anderholm, 1992). The Glorieta Sandstone contains about 30-50 ft (9-15 m, stratigraphic thickness) of well-cemented, light-gray quartzose sandstone that grades upsection into limestone of the San Andres Formation. The San Andres Limestone (Formation) is 66-130 ft (20-40 m) in stratigraphic thickness and consists of thin- to medium-bedded limestone, interbedded with medium-grained, well-cemented quartzose sandstone that is similar in composition to the underlying Glorieta Sandstone (Summers and Kottlowski, 1969). In the wells interpreted in this study (Appendix), the combined thickness of the Glorieta and San Andres Formations in boreholes range from about 197-387 ft (60-118 m) with an average thickness of about 295 ft (90 m).

Mesozoic

Mesozoic strata are divided into Triassic, Jurassic, and Cretaceous systems (Fig. 4). The Cretaceous section is divided into fine-grained formations and (mostly sandstone) members (Fig. 5).

Triassic

Triassic sedimentary rocks (Fig. 4) are not subdivided in this study, but they include widespread nonmarine lithostratigraphic units, such as the Moenkopi Formation and Chinle Group (usage of Lucas et al., 1999b). The Moenkopi Formation is the lowest unit of the Triassic succession in the study area. It is a laminated to thick-bedded, maroon-brown to dark-red, micaceous, fine-grained sandstone and siltstone intercalated with minor reddish-brown mudstone. The upper and lower contacts are unconformable. The Moenkopi Formation is about 98-220 ft (33-67 m) in stratigraphic thickness. The Chinle Group is divided into the Petrified Forest Formation and the underlying Agua Sarca Formation. The Petrified Forest Formation contains approximately 1312-1640 ft (400-500 m, stratigraphic thickness) of reddish-brown to orange-tan mudstone interbedded with thin subordinate lavender-gray sandstone, limestone-pebble conglomerate lenses, and gypsum. The contact with the underlying Agua Sarca Formation is gradational and regionally transgressive (diachronous). The Agua Sarca Formation contains 197-262 ft (60-80 m, stratigraphic thickness) of medium-grained, tan to white and light grayish-pink, thin- to medium-bedded quartz arenite and feldspathic arenite with minor interbedded reddish-brown mudstone. Interbedded mudstone is similar to the Petrified Forest Formation. In the wells interpreted in this study (Appendix), the combined thickness of the Triassic section in boreholes range from about 1122-1657 ft (342-505 m) with an average thickness of about 1362 ft (415 m).

Jurassic

The Jurassic succession includes the San Rafael Group and the Morrison Formation (Fig. 4). The Entrada, Todilto, and Summerville Formations are part of the San Rafael Group (usage of Lucas et al., 1995; and Lucas and Anderson, 1997). Other workers include the Summerville Formation with the lower part of the Morrison Formation (Picha, 1982; Menne, 1989; and Johnson et al., 2002). For this study, the Summerville Formation is included in the Morrison Formation, principally because distinctive beds in the Todilto Formation make a convenient stratigraphic break in the well data (*see below*).

The Entrada Formation consists of 70-115 ft (22-35 m, stratigraphic thickness) of variably colored (reddish-brown to grayish-pink, and gray-green and tan), very fine- to fine-grained, weakly cemented, cross-bedded, quartzose, eolian sandstone that disconformably overlies the Chinle Group. In the wells interpreted in this study (Appendix), the Entrada Sandstone ranges from about 56-128 ft (85-200 m) with an average thickness of about 154 ft (47 m).

The Todilto Formation consists of 56 ft (17 m, stratigraphic thickness) of a discontinuous, medium-gray to olive-gray, laminated, micritic limestone and white gypsum that rests disconformably on the Entrada Formation. The Todilto Formation has a distinctive geophysical-log signature (Fig. 6; high electrical resistivity and low gamma-ray counts), making it a very useful unit for subsurface correlation. For convenience, the top of the Todilto Formation is used to define the base of the Morrison Formation in this study. The Todilto Formation ranges from about 56-128 ft (17-39 m) with an average thickness of about 89 ft (27 m).

The Morrison Formation rests unconformably on the Todilto Formation. The Morrison Formation is locally subdivided into the Summerville Formation (formerly Recapture Shale Member, Lucas et al., 1995), Salt Wash Member, Brushy Basin Member, and Jackpile Member. The Summerville Formation has been mapped as part of the Morrison Formation. It has also been assigned to the San Rafael Group following Lucas and Anderson (1997). The Summerville Formation is approximately 325 ft (100 m) in stratigraphic thickness, and consists of purple-gray, red-brown, and green-gray mudstone interbedded with tan, gray, and greenish-gray, very fine grained sandstone.

Three members of the Morrison Formation are commonly recognized in northern New Mexico but are not differentiated in this study. Units of the Morrison Formation include the (upper) Jackpile, the (middle) Brushy Basin, and the (lower) Salt Wash (formerly Westwater Canyon Sandstone) members (Lucas et al., 1995). The uppermost Jackpile Sandstone Member is distinctive gray-white, kaolinitic, fine- to medium-grained sandstone with a thickness of about 70 ft (21 m, stratigraphic thickness) near Placitas, New Mexico. The (middle) Brushy Basin Member is a gray, green, and maroon mudstone and shale, with interbedded and intercalated gray to tan sandstone with a thickness of about 240 ft (73 m, stratigraphic thickness) near Placitas. The (lower) Salt Wash Member is a gray and light tan to yellowish white gray, medium-grained and weakly cemented sandstone with a thickness of 215 ft (66 m, stratigraphic thickness) near Placitas. The Morrison Formation pinches out towards the southern end of the MRGB (e.g., Cather, 1999). North of the Jurassic pinchout, the combined thickness of the Morrison Formation in wells ranges between 545 and 1043 ft (166-318 m) with an average thickness of about 869 ft (265 m).

Upper Cretaceous

Late Cretaceous sedimentation in northern New Mexico and southern Colorado was characterized by at least five transgressive-regressive cycles (Molenaar, 1983a; and Nummedal, 2004). For purposes of regional correlation, the complicated stratigraphy of Mesozoic section has been simplified to include only the Dakota Formation, Mancos Shale, Gallup Sandstone Member of the Mancos Shale, and Menefee Formation (Mesaverde Group). Other sandstone-bearing units within the Cretaceous succession have been locally delineated using well data. These include the Hosta and Dalton Sandstone Members and Gallup Sandstone Member of the Mancos Shale, and the Point Lookout Sandstone in the Mesaverde Group (Fig. 5).

The Dakota Formation is the lowest unit of the Cretaceous succession and is important because it represents the first transgressive shoreline sequence of the upper Cretaceous succession (Fig. 5). This unit is also important because it originally extended across much of the western interior and has been extensively contoured as a structural surface (Rocky Mountain Association of Geologists, 1972; Thaden and Zech, 1984; and Grant and Foster, 1989). The Upper Cretaceous Dakota Formation is a light-gray to brown, fine- to medium-grained, silica-cemented sandstone interbedded with olive-gray shale. The stratigraphic thickness of the Dakota Formation ranges from about 22-130 ft (7-40 m). The thickness of the Dakota Formation in wells ranges from about 131-394 ft (40-120 m), with an average thickness of about 292 ft (81 m).

The overlying Mancos Shale is a thick succession of dark-gray to olive-gray, shale, silty shale, and slightly calcareous shale with black limey mudstone and medium-bedded, calcareous sandstone. The Gallup, Hosta Dalton, and Semilla sandstones are used to locally divide the Mancos Shale into upper and lower members of the Mancos Shale (Fig. 5). Stratigraphic thickness of the lower Mancos Shale is variable and ranges from about 240-360 ft (73-110 m) between Placitas and the Hagan embayment (Picha, 1982). Stratigraphic thickness of the upper Mancos Shale is also variable, ranging from 850-1850 ft (260-565 m) between Placitas and the Hagan embayment (Picha, 1982). The total thickness of the Mancos Shale in wells ranges from about 1365-3107 ft (416-947 m), with an average thickness of about 1841 ft (561 m).

Numerous sandstone units are present in the Cretaceous succession. These include the Gallup Sandstone Member of the Mancos Shale and the Point Lookout Sandstone Member of the Mesaverde Group (Molenaar, 1983a). Other sandstone bodies are also present, and have been locally differentiated in this study. These thinner units include the Semilla Sandstone and the discontinuous sandstone of the Tocito Lentil of the Mancos Shale. The Semilla Sandstone is a 40 ft (12 m) thick interval of dark-gray shale and tan to yellow, planar laminated siltstone overlain by well-sorted, well-rounded, fine-grained and horizontally bedded sandstone found in the lower part of the Mancos Shale. The Semilla Sandstone pinches out just east of the study area (Fleming, 1989).

The Crevasse Canyon Formation contains the Dilco Coal, Dalton Sandstone, and Gibson Coal (Fig. 5). The Crevasse Canyon Formation overlies the Gallup Sandstone of the Mancos Shale and grades upsection into the Mesaverde Group. The combined stratigraphic thickness of the Crevasse Canyon Formation ranges from 513-1400 ft (156-427 m) in the northwestern part of the study area (Stone et al., 1983). In the Rio Puerco Valley, the Crevasse Canyon Formation may be quite thick. Two petroleum test wells (*xtowlan1* and *xtoarmt1*) encountered a thick succession of coal-bearing sediments in the interval between the Gallup Sandstone and Point

Lookout Sandstone (Appendix). The (lower) Dalton Sandstone represents a shoreline regression that joins the overlying transgressive (upper) Hosta Sandstone in the Hagan embayment (Black, 1982). Although the Hosta Sandstone is considered a transgressive tongue of the Mancos Shale, it is grouped with the Dalton Sandstone because of limited well control and observations that the Hosta and Dalton Sandstones merge towards the eastern edge of the study area (Fig. 5; Black, 1982; and Johnson et al., 2002). The Hosta and Dalton Sandstones are 213-377 ft (65-115 m) in stratigraphic thickness and consist of yellowish-gray to yellowish-tan, very fine- to medium-grained, weakly cemented, fossiliferous sandstone with olive-brown sandstone lenses.

The Mesaverde Group contains marine, marginal-marine, and nonmarine (fluvial) sandstone, shale, and siltstone with numerous coal-bearing intervals. In the study area, the Mesaverde Group includes the Menefee Formation and the Point Lookout Sandstone. The exposed stratigraphic thickness of the entire Mesaverde Group section is incomplete in the study area. The Point Lookout Sandstone is a grayish-tan to light-yellow, very fine- to fine-grained, massive, marine, quartz sandstone with limonitic sandstone lenses and interbedded gray shale; the upper and lower contacts are interfingering and gradational. The stratigraphic thickness of the Point Lookout Sandstone ranges from 15-240 ft (5-73 m) across the study area. The thickness of the Point Lookout Sandstone in well data ranges from about 98-230 ft (30-70 m). The Menefee Formation contains interbedded white to light-yellow, medium-bedded, well sorted, lenticular, cross-stratified, quartzose sandstone with siltstone, dark-gray to black, carbonaceous shale and brown to black lignitic coal beds. The Menefee is more than 1970 ft (600 m) in stratigraphic thickness where preserved in the study area. The overlying Lewis Shale is exposed in the San Juan Basin, but it is not present along the northwestern edge of the MRGB.

Cenozoic

Cenozoic strata were deposited in terrestrial environments and record three major geologic events (in decreasing age): the Laramide orogeny, a period of widespread volcanism, and later development of the Rio Grande rift.

Paleogene

Paleogene rocks (Fig. 4) are discontinuously exposed in the map area, mostly in the Hagan embayment and San Juan Basin. The Paleocene and Eocene Diamond Tail and Galisteo Formations record deposition by large east-flowing rivers that drained highlands of the southern Rocky Mountains (Lucas et al., 1997; and Cather 2004). Sandstone, conglomerate, and mudstone of the Baca Formation are recognized in the southern part of MRGB and southwest of the study area (Cather and Johnson, 1984; and Lozinsky, 1994).

The Diamond Tail Formation is mostly coarse-grained subarkosic to arkosic sandstone and conglomeratic sandstone with lesser amounts of drab, green, gray, and maroon mudstone. The Diamond Tail Formation disconformably overlies the Menefee Formation, and is disconformably overlain by the Galisteo Formation. The Diamond Tail Formation is interpreted to have been deposited within fluvial channels and broad floodplains between Albuquerque and Santa Fe, New Mexico (Lucas et al., 1997). The Diamond Tail Formation is not present along the western flank of the MRGB, but it reaches 1450 ft (442 m) in stratigraphic thickness at the type section in the adjacent Hagan embayment (Lucas et al., 1997).

The overlying Galisteo Formation is a mostly variegated red, green, purple and gray mudstone with intercalated thin beds of yellowish-brown, cross-bedded, arkosic sandstone and conglomerate. The Galisteo Formation is conformably overlain by Oligocene strata and disconformably overlain by the Santa Fe Group. The Galisteo Formation is discontinuously exposed along the western flank of the MRGB, where it is approximately 574 ft (175 m) in stratigraphic thickness (Lucas, 1982). The Galisteo Formation thickens to 2821-3212 ft (860-979 m) in the Hagan embayment (Lucas et al., 1997).

Oligocene volcaniclastic rocks

Fluvial deposition of the Baca, Diamond Tail, and Galisteo Formations (Fig. 4) was interrupted by widespread volcanism that persisted throughout late Eocene and Oligocene times. This period of extensive volcanic activity was part of the middle Tertiary *ignimbrite flare up* of the southwestern United States and Mexico (Lipman, 1992) and regional-scale denudation of the southern Rocky Mountains (Pazzaglia and Kelley, 1998). Oligocene volcanic and volcaniclastic rocks are discontinuously exposed along the southern and northeastern margins of the MRGB and along the flanks of the Mogollon-Datil volcanic field, exposed near the southern margin of the study area.

Oligocene rocks are not exposed along the Colorado Plateau-MRGB transition, but they are well exposed in the Hagan embayment (e.g., Espinaso Formation, Erskine and Smith, 1993), and thick successions are recognized in deep wells in the MRGB (e.g., unit of Isleta well #2, Lozinsky, 1994). These mostly volcanic-bearing deposits are thought to record the transition from largely Laramide compressional and transcurrent tectonism to extension associated with the Basin and Range and Rio Grande rift (e.g., Cather, 1992). The upper Eocene and Oligocene (*ca.* 27-39 Ma) Mogollon-Datil Groups were deposited as thick (up to 4.2 km in thickness) and arealy extensive aprons of rhyolitic ash-flow tuffs, basaltic lavas, and intermediate volcanic and volcaniclastic deposits that were associated with numerous volcanic centers in western and southwestern New Mexico (Osburn and Chapin, 1983). The unit of Isleta #2 is recognized in deep oil-test wells in the Belen and Calabacillas subbasins (Fig. 2). In boreholes, the unit of Isleta #2 is at least 7000 ft (2.2 km) thick and contains purplish-red to gray, volcanic-bearing subarkosic sandstone with mudstone interbeds (Lozinsky, 1994). Sources for the unit of Isleta #2 are not known, but the presence of abundant quartz detritus suggests fluvial or eolian deposition in a distal setting to Oligocene volcanic centers (Connell et al., 2007; and Cather et al., 2008). Local volcanic centers are not currently recognized, but could be buried within the MRGB.

Santa Fe Group

The Santa Fe Group (Fig. 4) represents the sedimentary and volcanic basin-fill of the Rio Grande rift (Chapin and Cather, 1994). Deposition of the Santa Fe Group within the Rio Grande rift began during the late Oligocene and ended with the incision of the Rio Grande Valley in the early Pleistocene (Spiegel and Baldwin, 1963; and Gile et al., 1981). Deposition occurred within broad fault-bounded basins (Bachman and Mehnert, 1978; Chapin and Cather, 1994; and Connell, 2004). Detrital composition of the Santa Fe Group reflects the composition of upland drainages, and varies from sedimentary to Cenozoic volcanic, and Proterozoic plutonic and metamorphic rock types (Lozinsky, 1994; Hawley et al., 1995; and Connell, 2004). The combined thickness of the Santa Fe Group fill ranges from about 10,000-16,400 ft (3-5 km) across the MRGB (Lozinsky, 1994; Connell, 2004; and Grauch and Connell, *in press*).

The Santa Fe Group is commonly divided into two or three subgroups (Hawley, 1978; Hawley, 1996; Cather and Chapin, 1994; and Connell, 2004). The lower Santa Fe Group records deposition within internally drained basins (bolsons) where streams derived from emerging basin-margin uplifts terminated onto broad alluvial plains or ephemeral or intermittent playa lakes and alluvial flats. As these internally drained basins filled with sediment they became topographically linked and allowed the ancestral Rio Grande system to flow through the basin and into southern New Mexico (Chapin and Cather, 1994; Connell et al., 2005; and Mack et al., 2006). Deposits of the upper Santa Fe Group generally mark the onset of fluvial integration and external drainage (Gile et al., 1981; and Connell et al., 2005). Deposits of the middle Santa Fe Group generally mark the transition from internal surface drainage to fluvial integration with adjacent basins (Connell et al., 2005).

In the MRGB, deposits of the lower and middle parts of the Santa Fe Group are divided into the Zia, Cerro Conejo, Arroyo Ojito, Popotosa, Tanos, and Blackshare Formations (Connell, 2004, 2008a). The Zia and Cerro Conejo Formations are dominated by well-sorted sandstone that is commonly well cemented with calcium carbonate. The Tanos and Popotosa Formations contain conglomerate near the basin margins and reddish-brown mudstone near basin depocenters. The Arroyo Ojito Formation contains a mixture of sandstone, conglomerate, and mudstone associated with large tributary drainages that head into the Colorado Plateau and Sierra Nacimiento (Connell et al., 1999).

In the study area, deposits of the upper Santa Fe Group are dominated by the Sierra Ladrones and Ceja Formations (Connell, 2004 & 2008a). The northeastern margin of the MRGB also contains deposits of the Cochiti Formation and Tuerto formation (or gravels, informal name). The Ceja Formation is a light-brown to very pale-brown and light yellowish-brown, moderately to well sorted, cobbly to bouldery sand and gravel with minor thin- to medium-bedded, interbeds of muddy sand and clay. The Ceja Formation is subdivided into three members based on stratigraphic position and deposit composition: an upper mesa-capping conglomeratic sand; a middle sand and gravelly sand; and two lower members that contain abundant mudstone and sandstone (Connell, 2008a). The Sierra Ladrones Formation represents deposits associated with the ancestral Rio Grande, prior to incision of the Rio Grande Valley. The axial-fluvial deposits of the Sierra Ladrones Formation interfinger with fluviatile deposits derived from the rift flanking uplifts (e.g., Connell, 2004).

Volcanic rocks

Igneous rocks from volcanic centers and lava flows cut across strata on the Colorado Plateau or are interfingered with Cenozoic sediments in the MRGB (e.g., Kelley and Kudo, 1978). Although these volcanic features dominate the landscape of the Colorado Plateau, they are typically fed by relative thin and narrow dikes (e.g., Hallett et al., 1997).

Quaternary alluvium

Surficial deposits are considered here to represent a group of generally thin sediments that mantle the ground surface and fill river valleys and arroyo floors. Quaternary alluvium (Fig. 4) is associated with modern and abandoned Pleistocene drainages that grade to modern and former levels of the Rio Grande. These poorly consolidated deposits typically consist of poorly to well sorted and stratified, clast- and matrix-supported alluvium, whose composition reflects rock types exposed in local upland tributary drainages. Stream-terrace deposits typically have an elongate planform shape and are associated with major tributaries to the Rio Grande. Alluvial deposits are generally less than 80-165 ft (25-50 m) in thickness and are commonly saturated with water.

Correlations

Regional correlations and stratigraphic thickness trends were established by matching stratigraphic horizons picked from wells, using the base of the Dakota Formation as a stratigraphic datum (Figs. 7 and 8). Of the 72 wells examined in this study, 52 lie within the study area (Fig. 3). Regional thickness trends were determined by projecting the stratigraphic picks from wells (Appendix) onto two vertical planes (Fig. 3), one north-south, and east-west. Figures 7 and 8 represent stratigraphic fence-diagrams that have been projected onto these two orthogonal planes in order to develop a consistent regional stratigraphic framework for refining the geologic cross sections (Plate 2). The stratigraphic picks were projected from wells within 22 miles (35 km) of each line to examine the consistency of unit elevations and to test for the presence of faults or unconformities through thickness variations. Wells denoted by an asterisk on Figures 7 and 8 were projected from a distance greater than 22 miles (35 km).

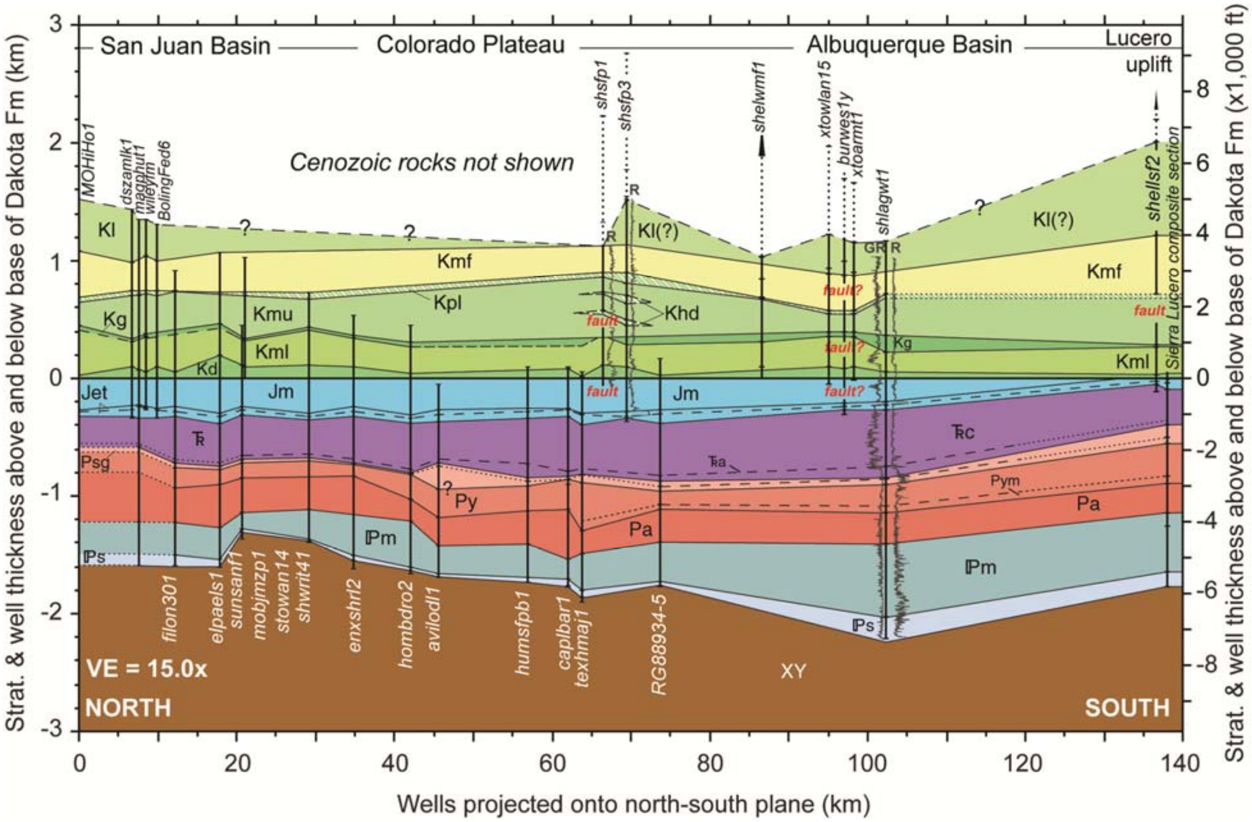

Figure 7. Wells projected onto north-south vertical plane (Fig. 3) using stratigraphic picks in the Appendix. Datum is the base of the Dakota Fm; vertical exaggeration (VE) = 15. Normal faulting is interpreted where unit thickness is anomalously thin. Borehole geophysical logs (GR = gamma ray; R = resistivity) shown for Shell Laguna Wilson Trust (*shlagwt1*), Shell Santa Pacific #1 (*shsfp1*) and #3 (*shsfp3*).

Wells that fully penetrate the Jurassic section are important for subsurface correlation because the gypsum-bearing Todilto Formation is easily recognized on borehole geophysical logs (Fig. 6). Anomalous variations in stratigraphic thickness among neighboring wells may indicate stratigraphic miscorrelation, major unconformities, or faults. Projecting the stratigraphic-fences onto north-south and west-east planes foreshortens the length of the original stratigraphic fence, but it also enhances apparent vertical discrepancies among closely grouped wells. The magnitudes of stratigraphic disconformity in Paleozoic and Mesozoic units are probably small among closely grouped wells, so anomalous variations in reported borehole thickness suggest unit miscorrelation or faulting.

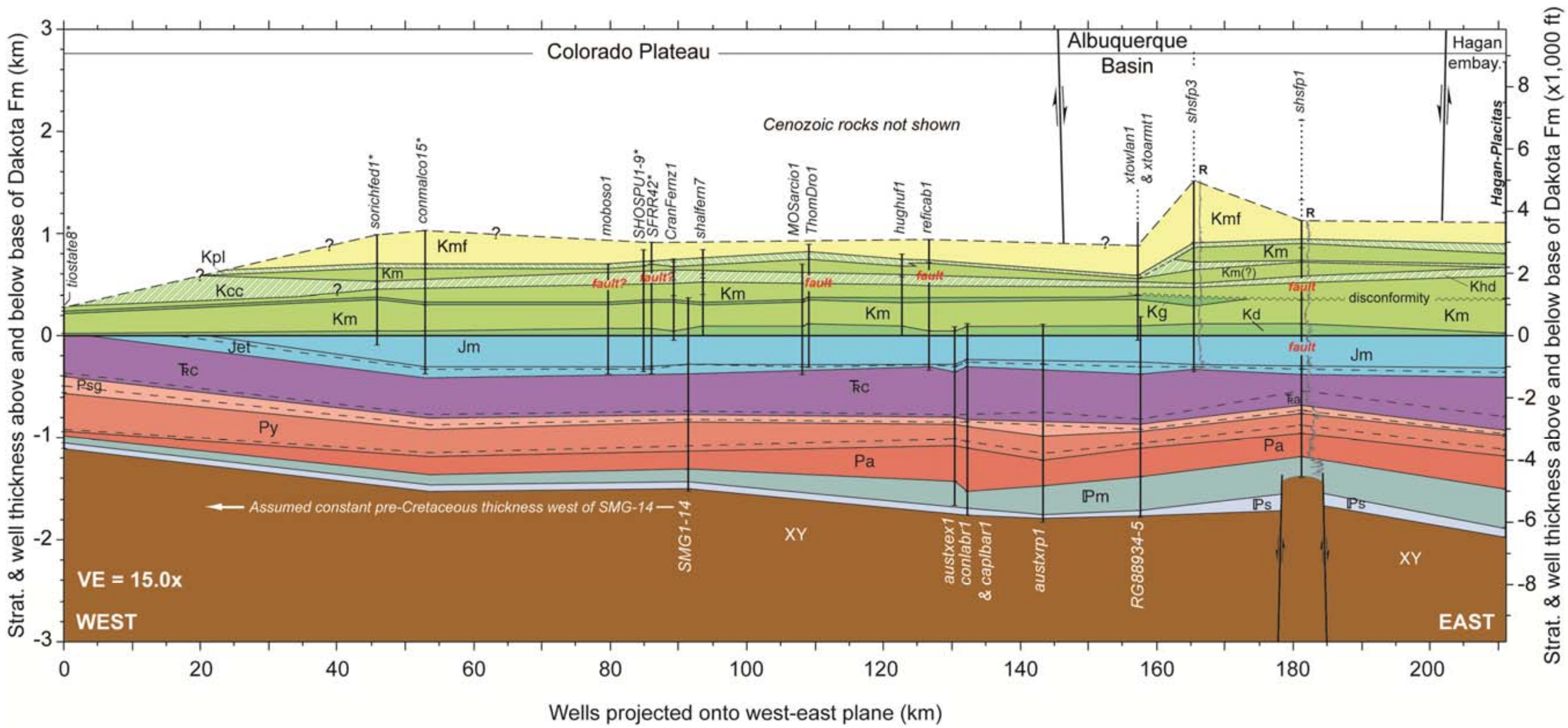

Figure 8. Wells projected onto north-south vertical plane (Fig. 3) using stratigraphic picks in Appendix. Datum is the base of the Dakota Fm; vertical exaggeration (VE) = 15. Asterisk (*) denotes wells projected more than 35 km into the plane of the stratigraphic fence. Normal faulting is interpreted where unit thickness is anomalously thin. Borehole geophysical logs (R = resistivity) shown for Shell Santa Pacific #1 (*shsfp1*) and #3 (*shsfp3*).

Data from wells showing anomalous variations in thickness were removed from the two projected fence diagrams (Figs. 7 and 8). With the exception of anomalous steepening on dip-meter logs, faults are generally difficult to interpret directly from borehole geophysical log data. Normal faulting can be recognized by anomalous decreases in unit thickness or removal of stratigraphic units, whereas reverse faulting thickens rocks encountered in boreholes. For example, the well RG88934-6 (Appendix) penetrated the Moquino fault. This fault was recognized by an absence of stratigraphic units and projection of the mapped fault trace into the borehole (Sengebush, 2008).

Cenozoic erosion removed much of the Cretaceous section above the Point Lookout Sandstone and Menefee Formations; however, regional trends in the Cretaceous stratigraphy are recognized through inter-well correlations (Figs. 7 and 8). The Gallup Sandstone locally divides the Mancos Shale into upper (*Kmu*) and lower (*Kml*) units on Figures 7 and 8. The Gallup Sandstone thins to the east and pinches out into a disconformity in the Mancos Shale near the western margin of the MRGB (Fig. 8). Sandstone of the Crevasse Canyon Formation (*Kcc*) thins eastward into the regressive Dalton Sandstone, which merges with the transgressive Hosta Sandstone just east of the study area.

Regional stratigraphic trends highlight the thinning of Triassic and Jurassic successions to the south (Fig. 7) and west (Fig. 8). The trends of these pinch-outs have been mapped regionally (Grant and Foster, 1989; and Cather, 1999). Jurassic strata thin to the south, where the Morrison Formation is completely eroded from the section near well *shellsf2* (Fig. 7) and the entire Jurassic succession has been pinched out between the Lucero uplift and Ladron Peak. Pennsylvanian strata pinch out in the Zuni uplift (e.g., Kues and Giles, 2004).

Hydrogeologic interpretations

Hydrogeologic characteristics of the stratigraphy exposed along the northern flank of the Sandia Mountains near Placitas, New Mexico, were made using interpretations of lithologic character and sparse well-performance data following Johnson et al. (2002). Stratigraphic units that are considered aquifer zones include the Gallup Sandstone of the Mancos Shale, Dakota Formation, Morrison Formation, Entrada Sandstone, San Andres Formation, Glorieta Sandstone, and Madera Group (Stone et al., 1983; and Johnson et al., 2002). Regional thickness trends for Mesozoic deposits in the adjacent San Juan Basin are available from the U.S. Geological Survey

Hydrologic Investigations Atlas 720 (Craigg et al., 1989, 1990; Dam et al., 1990a, b; Kernodle et al., 1989, 1990; Levings et al., 1990a, b; and Thorn et al., 1990a, b), and the New Mexico Bureau of Geology (Stone et al., 1983; and Johnson et al., 2002).

The Permian San Andres and Glorieta Formations represent regional-scale aquifers that are characterized by locally high transmissivity (Baldwin and Anderholm, 1992). These two units are bounded by less permeable strata of the underlying Pennsylvanian Madera Group and the overlying Triassic Chinle Group. The Madera Group forms an important aquifer system along rift-flanking uplifts (Titus, 1963, 1980; and Johnson et al., 2002); however, it has low permeability in the Colorado Plateau (Stone et al., 1983). Triassic rocks are dominated by mudstone and, with the exception of the Agua Sarca Formation, are generally not considered productive aquifer units (Johnson et al., 2002). Although the Chinle Group contains sandstone beds, it is dominated by mudstone and regionally represents a low-permeability unit (Baldwin and Anderholm, 1992; and Johnson et al., 2002).

Much of the Jurassic succession and the overlying Dakota Formation are dominated by coarse-grained sedimentary rocks that regionally comprise high-permeability (aquifer) zones (Craigg et al., 1989; Dam et al., 1990b; and Johnson et al., 2002). The overlying Cretaceous succession is dominated by shale and is regionally considered a low-permeability group of units (Stone et al., 1983), although high-permeability sandstone beds are recognized within the Cretaceous section (i.e., Dakota Formation, Gallup, Dalton, and Hosta Sandstones, and Point Lookout Sandstone). Much of the Cenozoic section contains the productive Santa Fe Group regional aquifer system, which has been investigated by previous workers (e.g., Hawley et al., 1995; and McAda and Barroll, 2002). Volcanic features are typically fed by relative thin and narrow dikes and probably do not impose strong barriers to regional groundwater flow. Large buried volcanic centers and lava flows (probably of Oligocene age) in the MRGB could locally influence deep groundwater flow.

The hydrogeologic character of the stratigraphic units listed on Figure 4 is based on the model parameters of Melis et al. (2011), who defined nine model layers. The upper three layers (1-3) represent the Cenozoic stratigraphic succession. Layer 4 represents low permeability Cretaceous sedimentary rocks that overlie the Dakota Formation. Layer 5 contains the Dakota Formation and Jurassic strata. Layer 6 contains the Triassic Chinle Group. Layer 7 contains the San Andres and Glorieta Formations. Layer 8 contains the Yeso Formation, and layer 9 represents the Abo Formation. Rocks below the base of the Abo Formation were not modeled by Melis et al. (2011). The fault juxtaposition analysis divided the model layers of Melis et al. (2011) into conduits and seals: layers 5 and 7 represent permeable zones, and the remaining zones are defined as seals (i.e., impermeable). The impermeable layers of the Melis et al. (2001) model locally contain zones of moderate or high permeability (e.g., Johnson et al., 2002).

STRUCTURAL GEOLOGY

The study area contains numerous faults that were mapped by previous workers (Fig. 9A). These faults exhibit mostly normal displacements and are most abundant near uplifts and along the edges of the MRGB (Plate 1 and Fig. 10). The northwestern margin of the MRGB contains numerous faults, cutting Cretaceous and Cenozoic strata, that lie within a broad eastward (dextral) step between the Lucero uplift and Sierra Nacimiento (Kelley, 1982) called the Laguna bench (Russell and Snelson, 1994). The western flank of the Laguna bench is defined by faults of the Rio Puerco fault zone and the Ignacio monocline. The eastern edge of the Laguna bench is broadly defined by traces of the San Ysidro and South Garcia faults (Russell and Snelson, 1994).

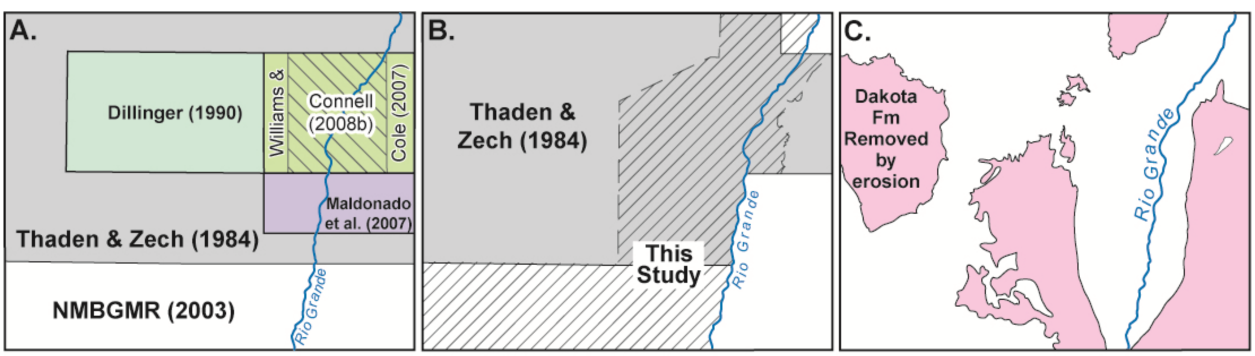

Figure 9. Sources of geologic data used for the generalized geologic map on Plate 1. A: Fault and fold data sources; geologic units from NMBGMR (2003). B: Data sources for structure-contour map of the Dakota Formation (Thaden and Zech, 1984), and areas interpreted in this study. C: Pink shading approximately denotes areas where the Dakota Formation has been removed by erosion.

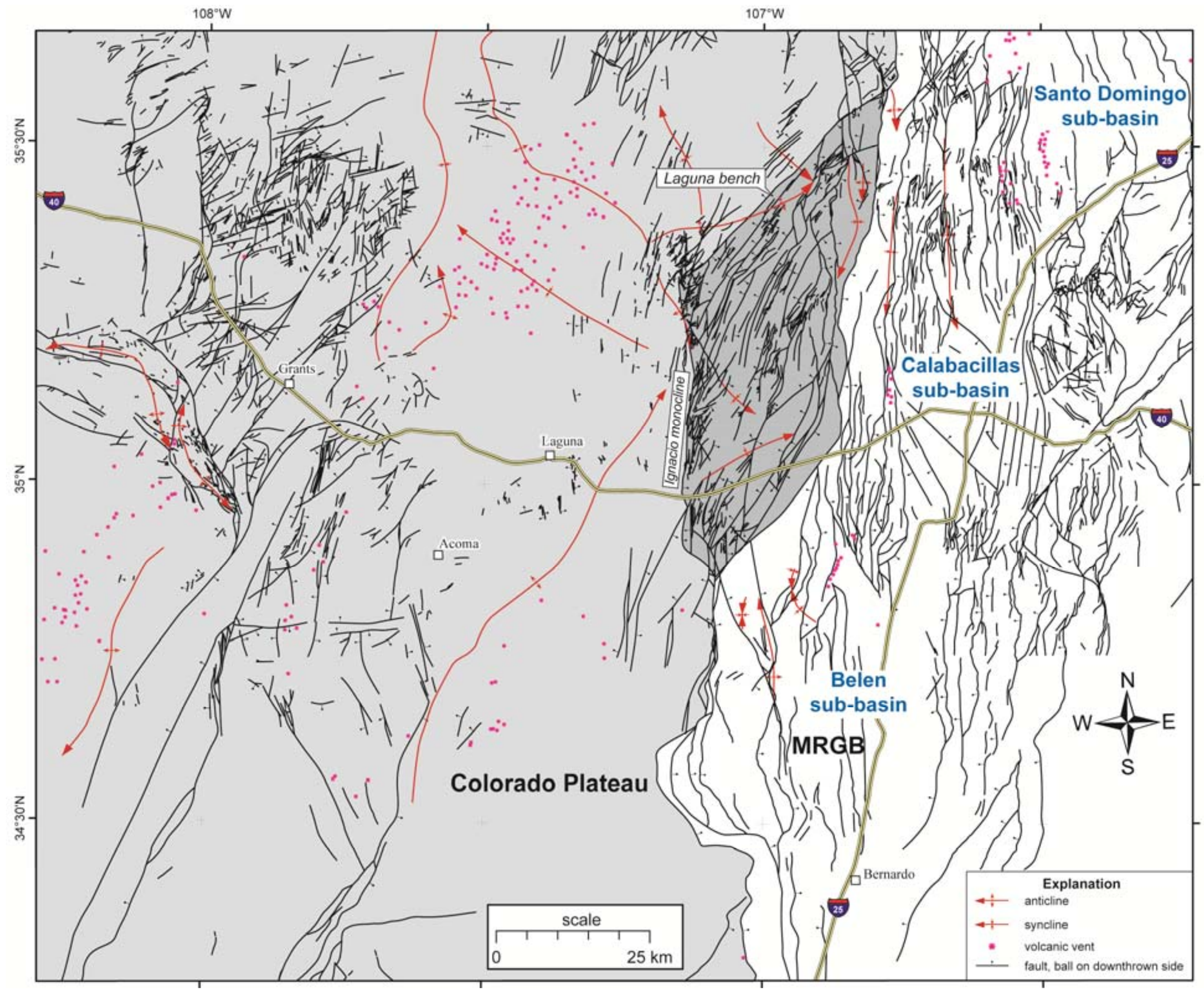

Figure 10. Map of faults and folds in study area; normal faults denoted by ball on down-thrown side. Shading denotes approximate areal extent of the Colorado Plateau; darker shading denotes the Laguna bench. Names of MRGB subbasins are shown in blue.

Intrabasinal structures have important geometric implications regarding the distribution of subsurface recharge sources along the western flank of the MRGB, which is segmented into the Santo Domingo, Calabacillas, and Belen subbasins (Fig. 10). The Calabacillas subbasin has a predominantly eastward tilt and forms an eastward-dipping faulted homocline that includes the Laguna bench (Fig. 11, cross section D-D’). This eastward tilt of the Calabacillas subbasin serves to bury the Paleozoic succession deep beneath the MRGB, where few springs are recognized in Cretaceous rocks (Melis et al., 2011). In contrast, the southern part of the MRGB (Belen subbasin) contains at least two antiformal features, one of which is buried beneath the Rio Grande (Fig. 11, cross-section E-E’). The southwestern flank of the Belen subbasin forms a north-plunging anticline along the Lucero uplift that has been extensively cut by normal faults. The rift-flanking uplifts tilt away from the MRGB, exposing upper Paleozoic rocks along the eastern flank of the Lucero uplift, where abundant springs are present (Kelley et al., 1976). The shift from east-tilted stratal geometry of the Calabacillas subbasin to the more complicated structure of the Belen subbasin occurs where the Rio San Jose enters the MRGB. It is possible that the Rio San Jose may have exploited the low topographic relief created by this transition.

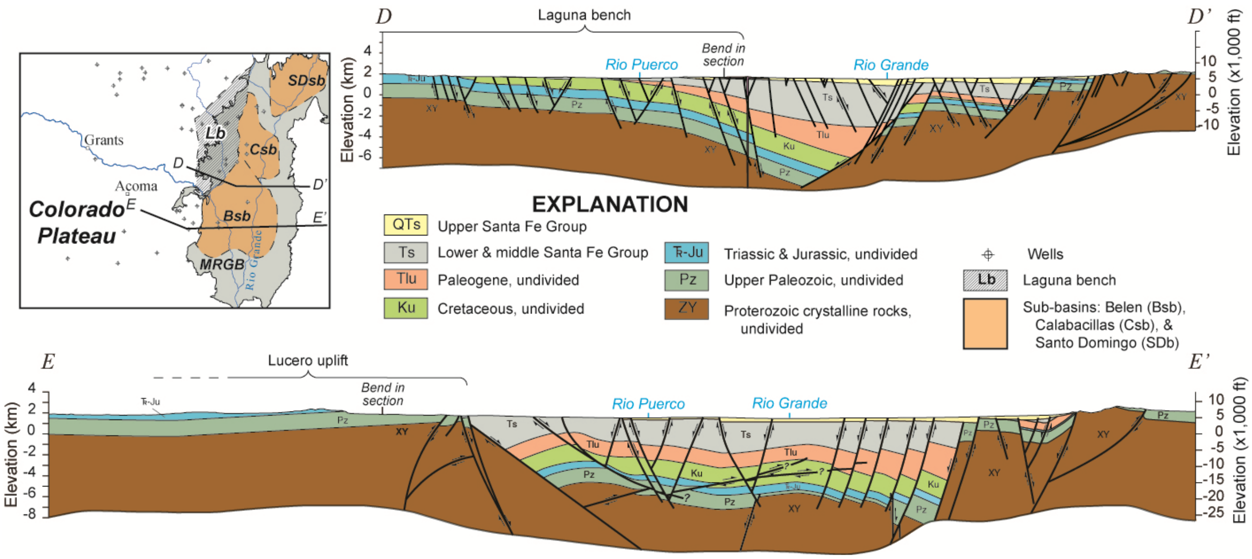

Figure 11. Simplified geologic cross sections (D-D’ and E-E’ on Plate 1) across the Colorado Plateau-MRGB transition (no vertical exaggeration). Inset map illustrates well locations and subbasin boundaries.

An understanding of the structural relief on top of the Precambrian is necessary to delineate the structure of basins and uplifts and distribution and thickness of stratigraphic units in the study area. Foster and Stipp (1961) published a structural relief map of the Precambrian surface that was refined by Broadhead et al. (2009). The structure-contour map of the Precambrian by Broadhead et al. (2009) required only slight adjustments along the western margin of the MRGB (in the Rio Puerco Valley, near the *shlagwt1* well, Appendix) to agree with the sparse well coverage and data (Fig. 12).

An important map of the regional structure was compiled by Thaden and Zech (1984), who contoured the base of the Dakota Formation using outcrop and borehole controls. This structure-contour map is useful because it defines the Cretaceous-Jurassic boundary across most of the study area. This map was drawn using a contour interval of 100 m, making it one of the most precise structure-contour maps available. Plate 1 shows the areal extent of the sub-Dakota surface and exposures of the Morrison and Dakota Formations from the State Geologic Map (NMBGMR, 2003). In addition to the faults compiled by Thaden and Zech (1984), the structure-contour map on Plate 1 also includes faults mapped by later studies (Fig. 9A). The elevation of the basal Dakota surface compares favorably with the well data interpreted for this study (Plate 1). Improvements to the Thaden and Zech compilation are the results of later detailed mapping of faults along northwestern margin of the MRGB, and incorporation of newer petroleum and water exploration wells drilled since 1984 (Appendix). The structure contours of original Thaden and Zech compilation were re-interpreted east of the Ignacio monocline area and through the Rio Puerco Valley (Figs. 9B and 10). Well control for the base of the Cretaceous section is sparse in the southern part of the study area. Structure contours of the base of the Dakota Formation are speculative south of the area covered by the Thaden and Zech compilation.

A simplified structure-contour map of the base of the Dakota Formation (Fig. 13) was redrawn from Plate 1, with elevation units in feet to facilitate comparisons with the structure contour map of the Proterozoic basement. Regions where erosion has removed the Dakota Formation are illustrated on Figure 9C. Although no longer present, the contours of the eroded Dakota Formation are important because they illustrate areas where modern recharge to the Dakota may occur. These contours also represent the pre-Cretaceous surface that illustrates areas subjected to later (mostly Laramide) uplift and erosion. The sub-Dakota contours also highlight a wide southeast-plunging syncline in the Laguna bench.

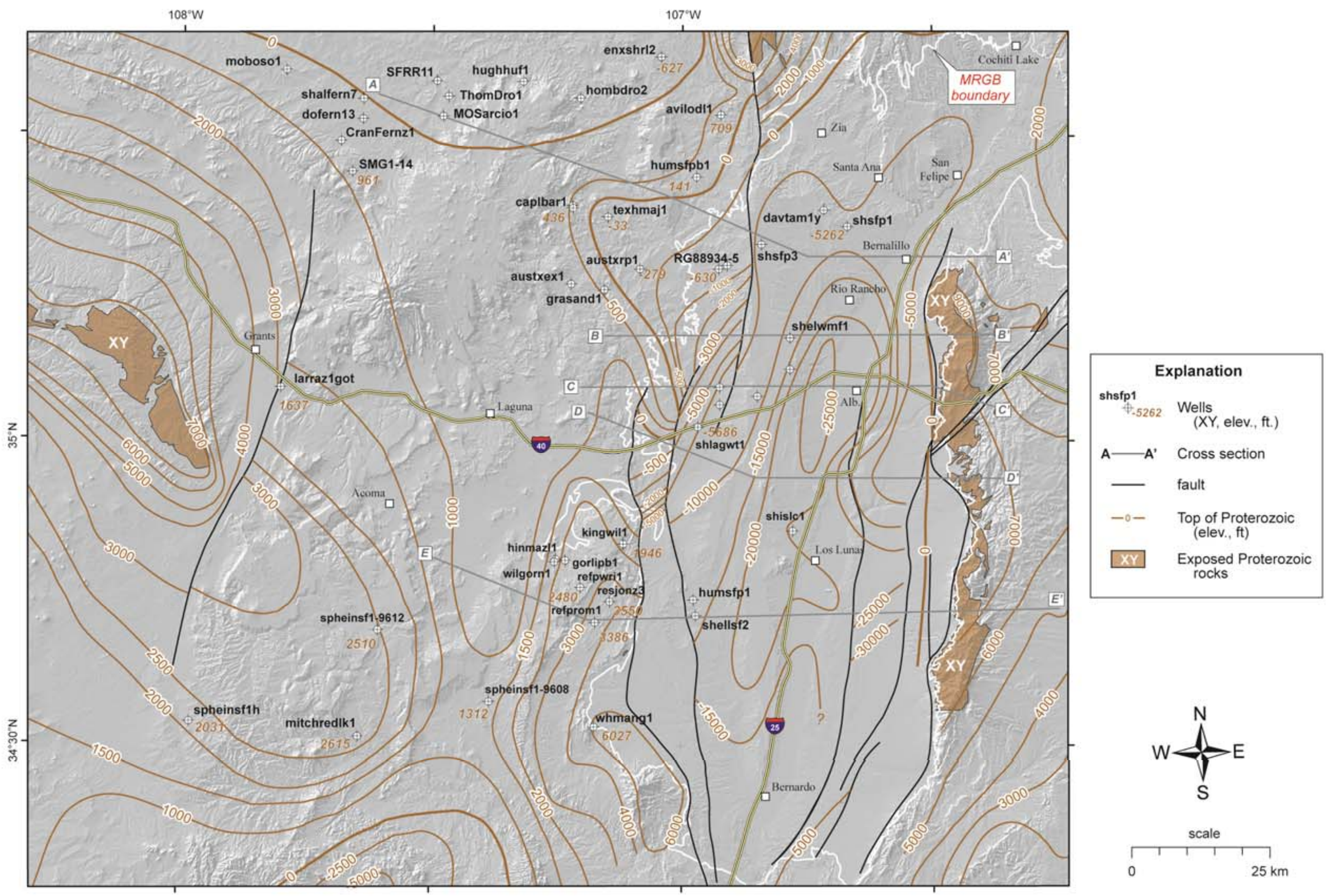

Figure 12. Structure contour map of the elevation of the top of Proterozoic (Precambrian) crystalline rocks (modified from Broadhead et al., 2009). Contour interval in 500 ft increments above sea level; 1000- and 5000-ft contour intervals below sea level.

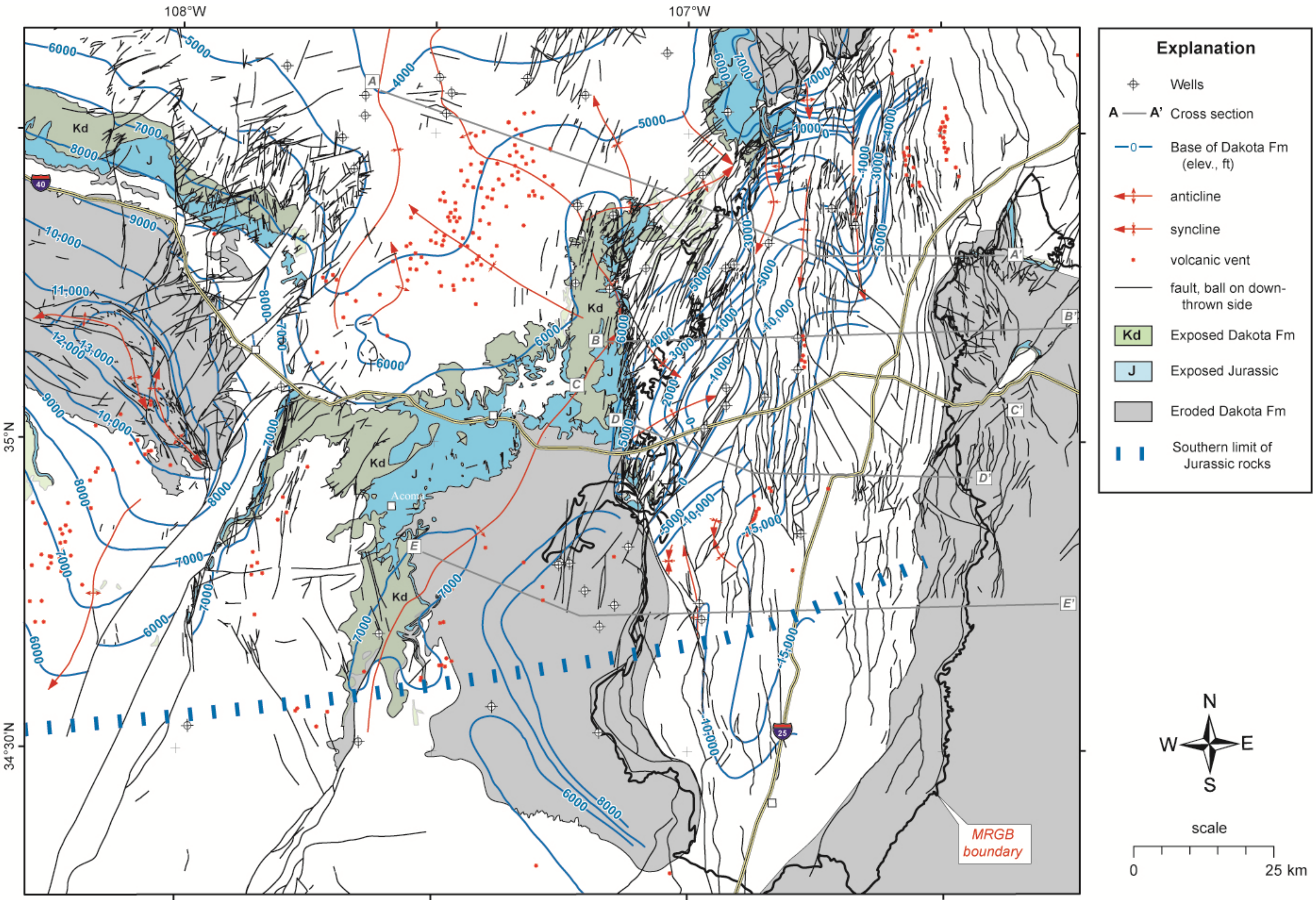

Figure 13. Structure contour map (re-contoured in feet) of the base of the Dakota Formation (based on data from Plate 1), including the southern limit of Jurassic rocks (Grant and Foster, 1989).

Refinements to the thickness of the Santa Fe Group basin-fill were made using results of a 3D geophysical inversion that exploited a natural break in bulk density between the Santa Fe Group and older rocks (Grauch and Connell, *in press*). This inversion method does not deal with faults explicitly, thus major structures were inferred using regional the map compilation (Plate 1). A simplified version of a structure contour map of the base of the Santa Fe Group shows that the basin-fill considerably thickens east of the Laguna bench, across the San Ysdiro fault zone (Fig. 14).

The geologic cross sections (Plate 2) delineate major structures and key stratigraphic units in the subsurface that are displaced by major faults. Geologic cross sections were originally constructed across parts of the MRGB (Russell and Snelson, 1994; Maldonado et al., 2007; and Connell, 2008b; Melis, 2009; and Grauch and Connell, *in press*). These cross sections were extended west onto the Colorado Plateau, and have been vertically exaggerated by a factor of two in order to highlight details of the structure and stratigraphy. Cross sections D-D' and E-E' have been simplified and shown without vertical exaggeration on Figure 11 to illustrate basin structure.

Geologic cross sections A-A', B-B', and C-C' were modified from a compilation of the geology of the Albuquerque-Rio Rancho metropolitan area (Connell, 2008b). Cross section A-A' was extended west onto the Colorado Plateau, and ended near the southern margin of the San Juan Basin. This cross section required modification west of the Ziana strain-accommodation zone (Kelley, 1977; and Stewart et al., 1998) because the initial attempts at building this cross section (A-A') did not consider thinning of the Mesozoic section by normal faults suggested by Black (1981). Cross section B-B' and C-C' were extended onto the eastern flank of the Ignacio monocline. Cross section D-D' was modified and redrawn from Line 65 of Russell and Snelson (1994), and incorporated structural interpretations by Maldonado et al. (1999 and 2007) and Grauch and Connell (*in press*). This cross section was extended northwestward onto Mesa Gigante within the Colorado Plateau. Cross section E-E' was modified from Grauch and Connell (*in press*) and extended northwest across the Lucero uplift.

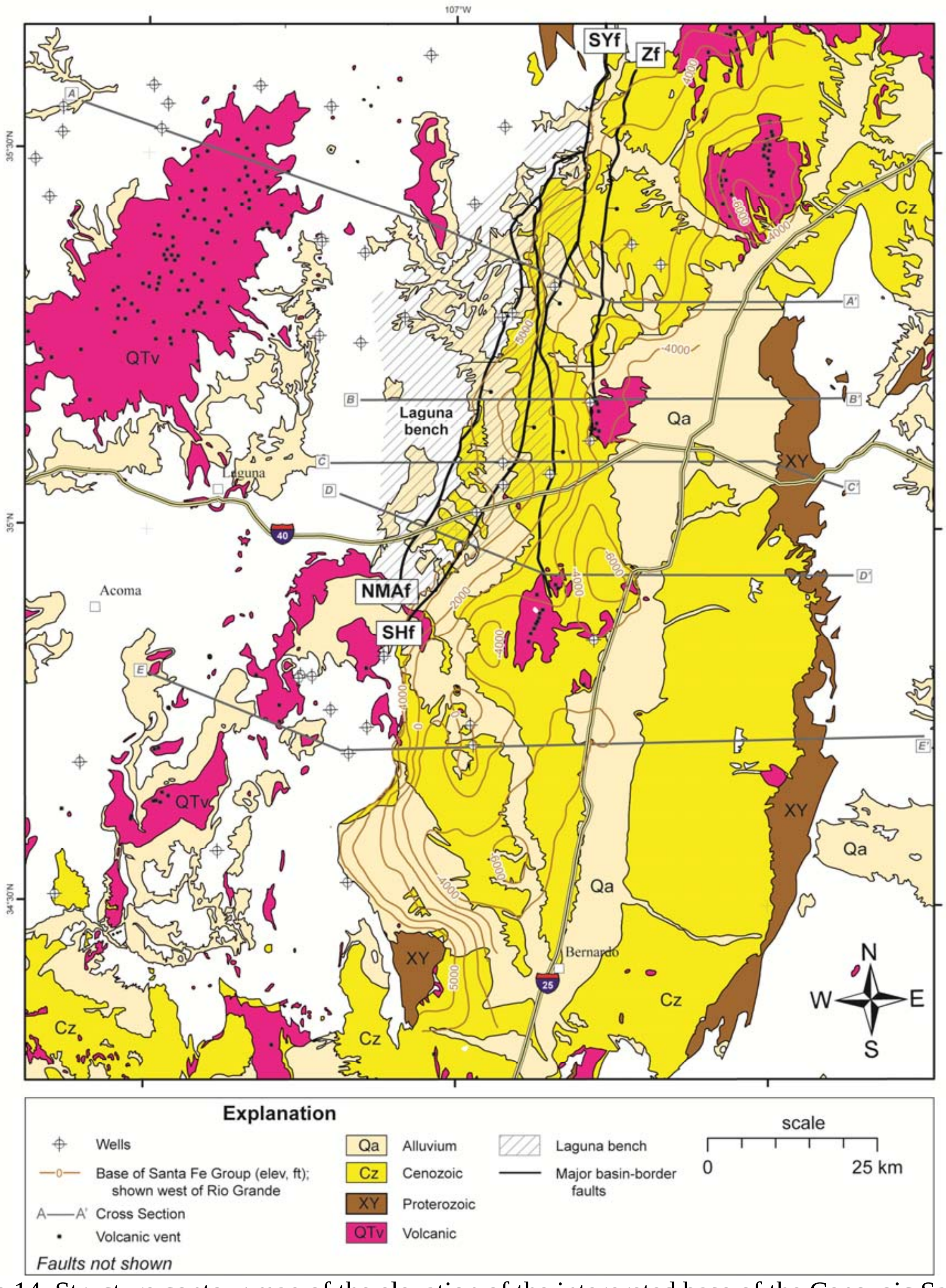

Figure 14. Structure contour map of the elevation of the interpreted base of the Cenozoic Santa Fe Group west of the Rio Grande; 1000-ft contour intervals based data from Grauch and Connell (*in press*). The figure covers the eastern part of the study area. Selected basin bordering faults include the Zia (Zf), San Ysidro (SYf), Tenorio-Garcia-Sand Hill (SHf), and Navajo-Moquino-west Apache (NMAf) fault zones.

Fault juxtaposition

Fluid flow across faults can be inhibited by: 1) juxtaposition of strata of differing permeability; 2) generation of fault material having a lower permeability than the original rock or sediment; and 3) cementation or mineralization of the fault zone (Knipe, 1993 and 1997; Caine, 1996; Rawling et al., 2001; and Doughty, 2003). Along-strike variations in displacement across *en echelon* normal faults can result in monoclinal flexures called relay ramps (Fig. 15). These relay ramps can form where the displacement of basin-border faults decrease and become less-prominent intrabasinal faults (Kelley, 1982). Such structural ramps may be hydrogeologically important because they can limit the flow of groundwater into the basin fill through the juxtaposition of permeable stratigraphic units across faults.

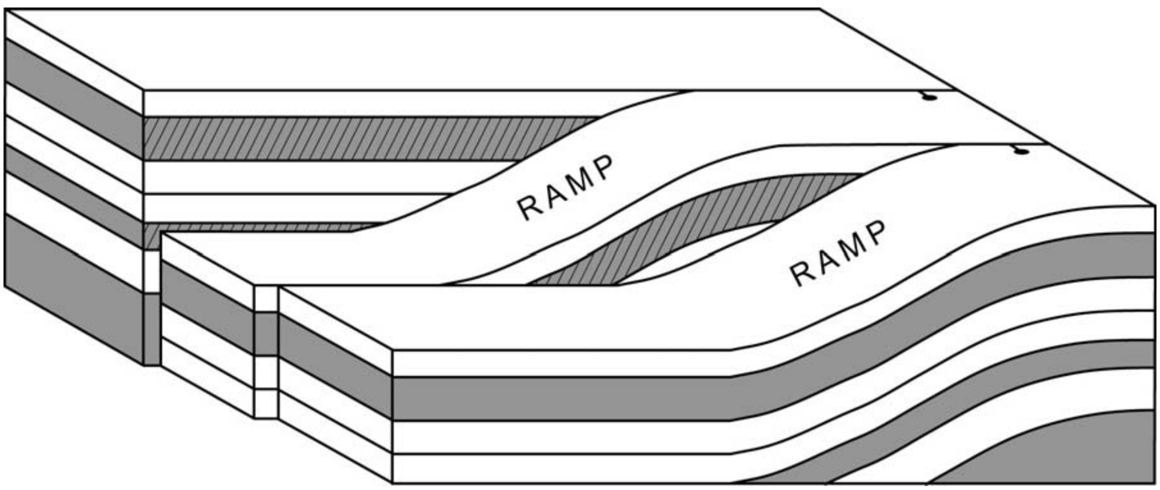

Figure 15. Schematic diagram illustrating variations in displacement across relay ramps formed by overlapping *en echelon* normal faults (modified from Kelley, 1982). Relay ramps form as displacement increases, resulting in a series of stepped monoclinal flexures that juxtapose different stratigraphic units along fault traces. Hachured lines denote regions along the fault face where groundwater-conduit windows may form.

To better understand how groundwater from the Colorado Plateau move through fault zones and enter the MRGB, the spatial distribution of juxtaposition seals and conduits was mapped into the subsurface by projecting the hanging-wall and footwall stratigraphy onto fault planes to estimate the amounts of overlap among permeable and impervious units (e.g., Knipe, 1993 and 1997). A preliminary geometric examination of fault juxtaposition was completed for three groups of fault zones (Fig. 16). A detailed analysis of fault-zone permeability is beyond the scope of this study. To do this, two cross sections were drawn along the trace of a fault, and stratigraphic units were projected onto the fault plane (Figs. 17-19): one for the footwall (upthrown) face; and a complementary cross section for the hanging-wall (downthrown) face of the fault. Deposits that intersect the fault plane are defined as either conduit or seal windows (Fig. 4). Conduits were defined as high-permeability layers (aquifer zones) in the groundwater-flow model of Melis et al. (2011). These aquifer zones were grouped into Cenozoic strata (Layers 1-3), the Dakota Formation and Jurassic strata (Layer 5), the Glorieta Sandstone and San Andres Limestone (Layer 7), and the Yeso Formation (Layer 8). Fault barriers are interpreted where impervious units are juxtaposed across a fault. Conduit windows are defined where permeable intervals are juxtaposed across a fault. It is likely that coarse-grained or fractured beds within seals may locally possess zones of high horizontal hydraulic conductivity (e.g., Caine, 1996; and Rawling et al., 2001). Conduit windows may locally contain fine-grained material that has been smeared across the fault plane (e.g., Doughty, 2003). The effects of fault-zone permeability were not incorporated into the fault-juxtaposition analyses.

The structure-contour map of the base of the Dakota Formation (Plate 1) and geologic cross sections (Plate 2) provide stratigraphic and structural control to project stratigraphic horizons into the three major basin-margin fault zones examined herein (Fig. 16): San Ysidro; Tenorio-Garcia-Sand Hill; and Navajo-Moquino-west Apache fault zones. These juxtaposition analyses relied on the regional stratigraphic thickness trends determined from borehole data (Figs. 7 and 8) and (because of smoothing) may not precisely match unit depths along fault strike (Plate 2). Numerous faults define the Ziana strain-accommodation zone in an area lacking sufficient well control for a complete structural analysis of the Zia fault zone; however, preliminary analyses suggest only minor displacement across this structure (S.D. Connell, unpubl. data).

The San Ysidro fault zone is about 95-km long and defines much of the northeastern edge of the Laguna bench (Fig. 10). The northern end of the San Ysidro fault zone lies in the Jemez Mountains and Sierra Nacimiento, where it juxtaposes Pennsylvanian and Proterozoic rocks of the Sierra Nacimiento against Oligocene and Permian rocks along the northern edge of the MRGB (Fig. 17). The San Ysidro fault zone dies out to the south into a zone of overlapping *en echelon* faults near Wind Mesa, about 5 km east of the Cat Mesa fault. A south-verging

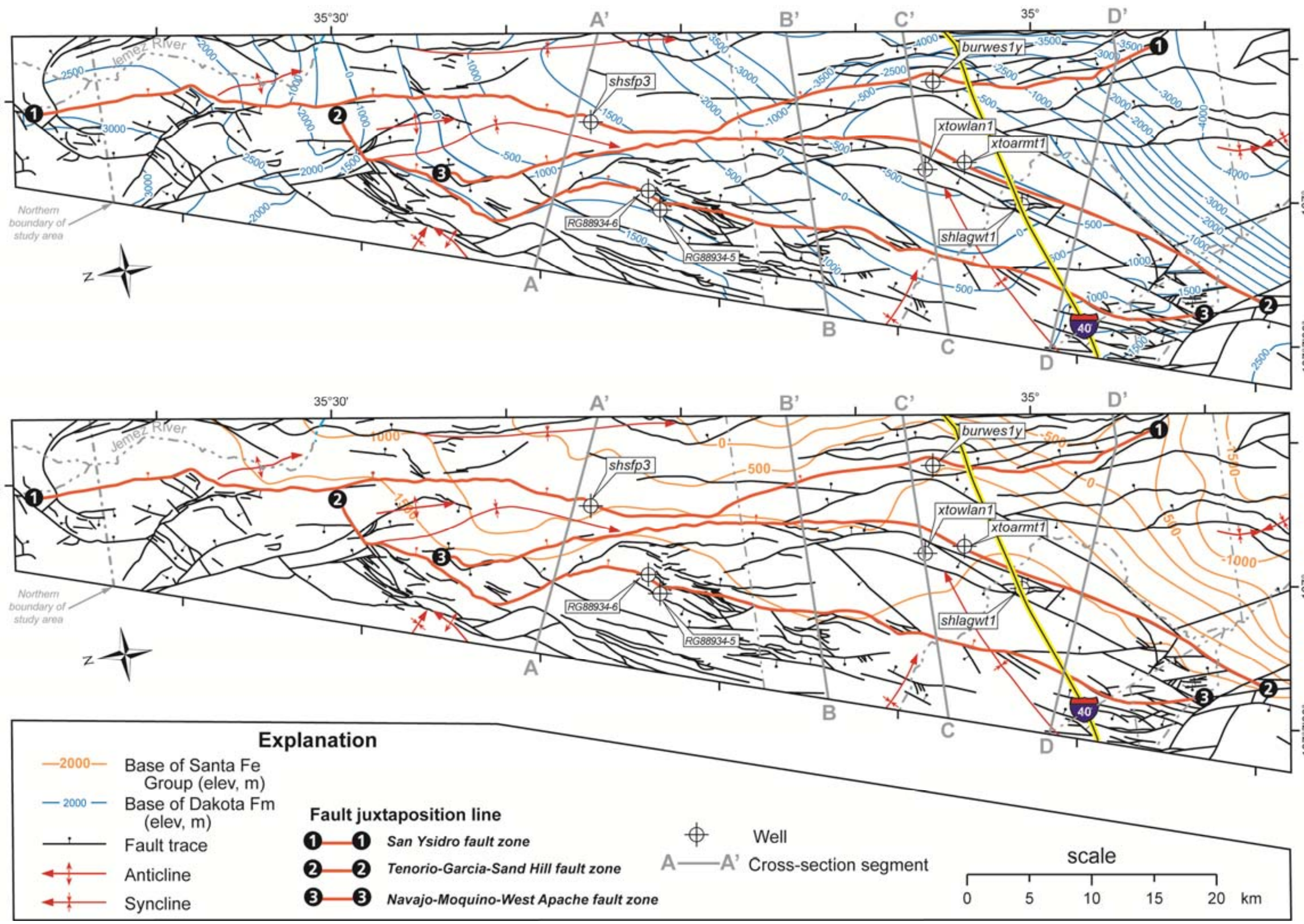

Figure 16. Structure maps, illustrating structure-contours (elev.: meters), and traces of faults that define the western margin of the MRGB, highlighting the San Ysidro (1), Tenorio-Garcia-Sand Hill (2), and Navajo-Moquino-Apache (3) fault zones. Top: Structure contours of the base of the Dakota Formation (blue; contour elevation in meters). Bottom: structure contours of the base of the Santa Fe Group (orange; contour elevation in meters).

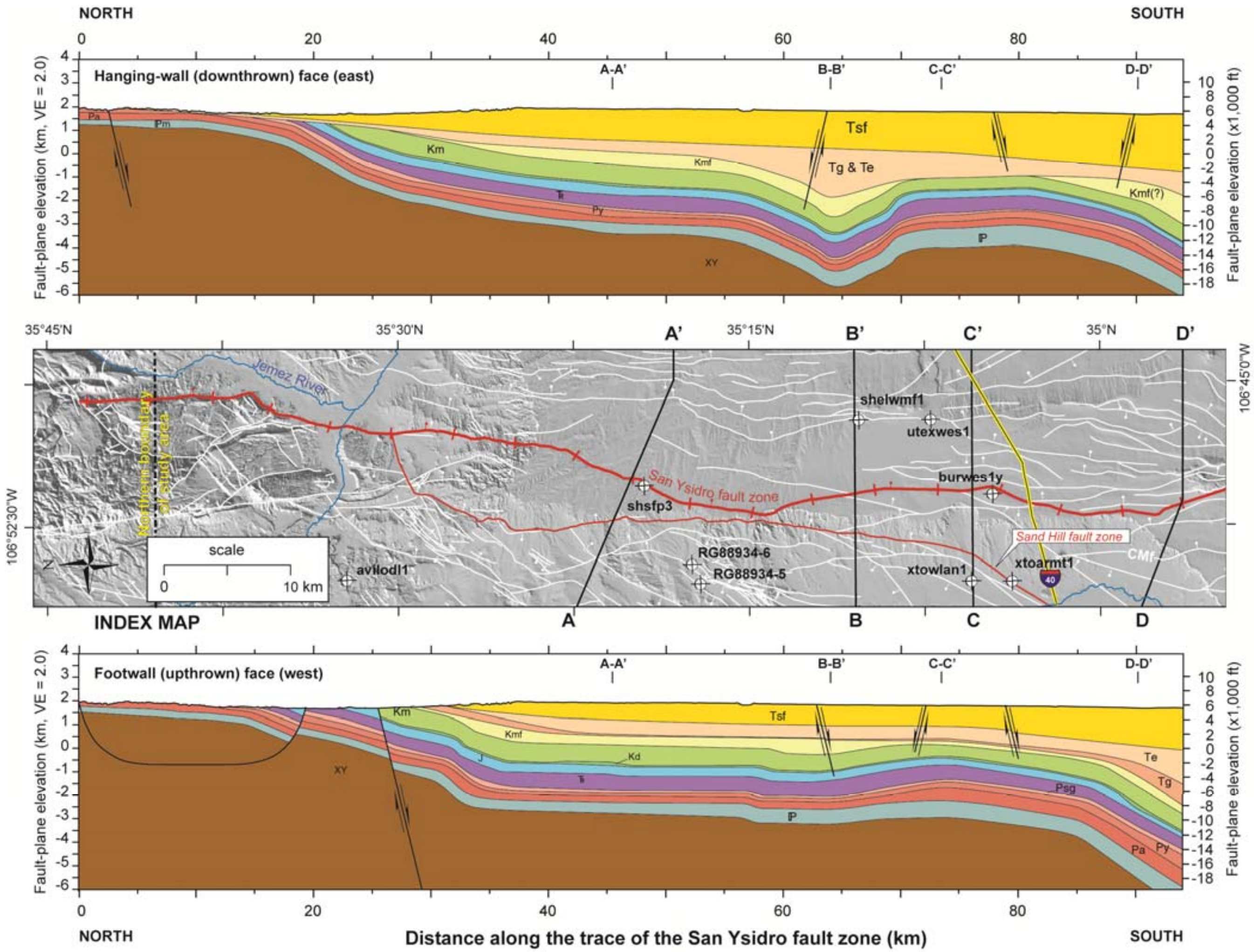

Figure 17. Map and cross sections along the trace of the San Ysidro fault zone, illustrating the juxtaposition of map units across faults. Top: cross section along trace of fault, illustrating intersection of major stratigraphic units onto downthrown (hanging-wall) face of fault. Middle: index map of faults, including the Cat Mesa fault (CMf), nearby wells, and cross sections (Plate 2). Bottom: cross section along trace of fault, illustrating intersection of major stratigraphic units onto the upthrown (footwall) face of the fault.

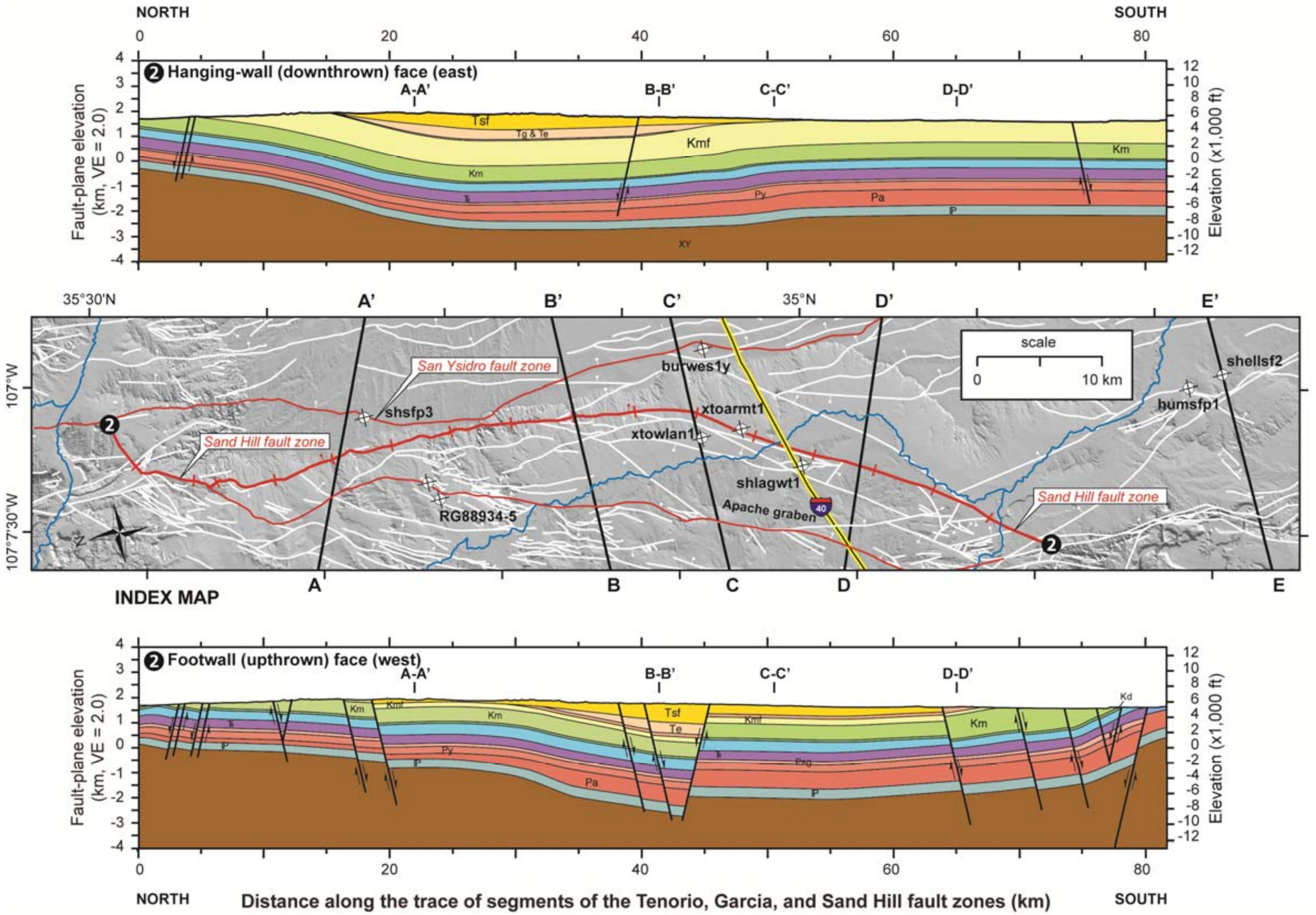

Figure 18. Map and cross sections along the trace of the Tenorio, Garcia, and Sand Hill fault zones, illustrating the juxtaposition of map units across faults. Top: cross section along trace of fault, illustrating intersection of major stratigraphic units onto downthrown (hanging-wall) face of fault. Middle: index map of faults, including nearby wells and cross sections (Plate 2). Bottom: cross section along trace of fault, illustrating intersection of major stratigraphic units onto the upthrown (footwall) face of the fault.

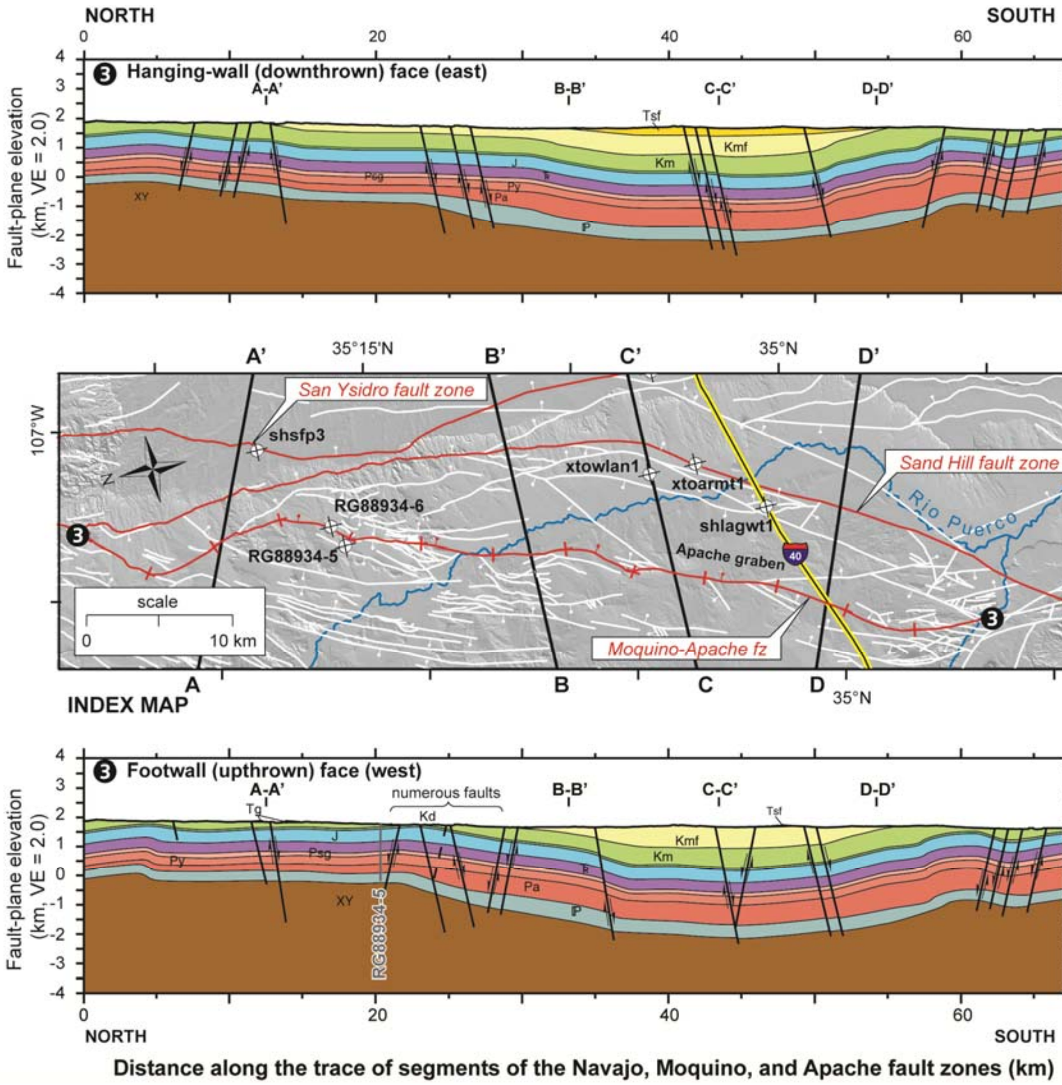

Figure 19. Map and cross sections along the trace of the Navajo, Moquino, and Apache (Moquino-Apache) fault zones, illustrating the juxtaposition of map units across faults. Top: cross section along trace of fault, illustrating intersection of major stratigraphic units onto downthrown (hanging-wall) face of fault. Middle: index map of faults, including nearby wells and cross sections (Plate 2). Bottom: cross section along trace of fault, illustrating intersection of major stratigraphic units onto the upthrown (footwall) face of the fault.

monoclinal flexure (resembling a relay ramp) is interpreted between the Sand Hill and Zia fault zones (Fig. 14), where geologic mapping shows an overall southward tilt and thickening of the Santa Fe Group.

The Tenorio-Garcia-Sand Hill fault zones contain basin-bounding normal faults that have been grouped for this juxtaposition analysis (Fig. 18). The combined length of this fault zone is about 82 km. The northern end of this fault zone connects to the San Ysidro fault zone. The

Tenorio fault marks the western structural boundary of the MRGB just south of the junction with the San Ysidro fault zone. The Navajo-Moquino-Apache fault zones represent a set of *en-echelon* basin-bounding normal faults that have been grouped for this juxtaposition analysis (Fig. 19), and represents the westernmost series of faults examined for this study. The combined length of this fault zone is about 66 km. The Navajo-Moquino-Apache defines the western limit of thick Cenozoic basin fill along the west edge of the Apache graben of Kelley (1977) and may connect with the southern projected end of the Sand Hill fault zone.

Conduit-seal distributions

Figure 20 shows cross sections of the hanging-wall (basinward) faces of the San Ysidro, Tenorio-Garcia-Sand Hill, and Navajo-Moquino-west Apache fault zones (Fig. 16). The spatial distribution of conduits is discontinuous and is related to regional deformation of strata and localized deformation across fault zones. Most of the San Ysidro fault lies within the MRGB, where Cenozoic aquifer units are juxtaposed south of the Jemez River. A south-facing relay ramp forms small conduit windows between Jurassic-Dakota and Permian units. The San Ysidro fault and south-verging relay-ramp may also control the location of a hydrogeochemical-zone boundary in the MRGB aquifer suggested by Plummer et al. (2004). The juxtaposition of synclinal strata on the basin-facing part of the Tenorio-Garcia-Sand Hill fault zone forms a narrow conduit in the Cenozoic basin-fill, and discontinuous conduit windows in the Jurassic-Dakota aquifer zone (Fig. 20). Permian aquifer units are discontinuously connected along the Tenorio-Garcia-Sand Hill fault zone. The hanging-wall face of the Navajo-Moquino-Apache fault zone locally defines the western limit of the Santa Fe Group, and thus marks the structural boundary of the MRGB. This fault zone also contains a broad syncline between the Sierra Nacimiento and Lucero uplifts. The smaller-magnitude displacements across this fault zone result in wide conduit windows in the Mesozoic and Permian aquifer zones that may permit larger groundwater flow from the Colorado Plateau into the MRGB.

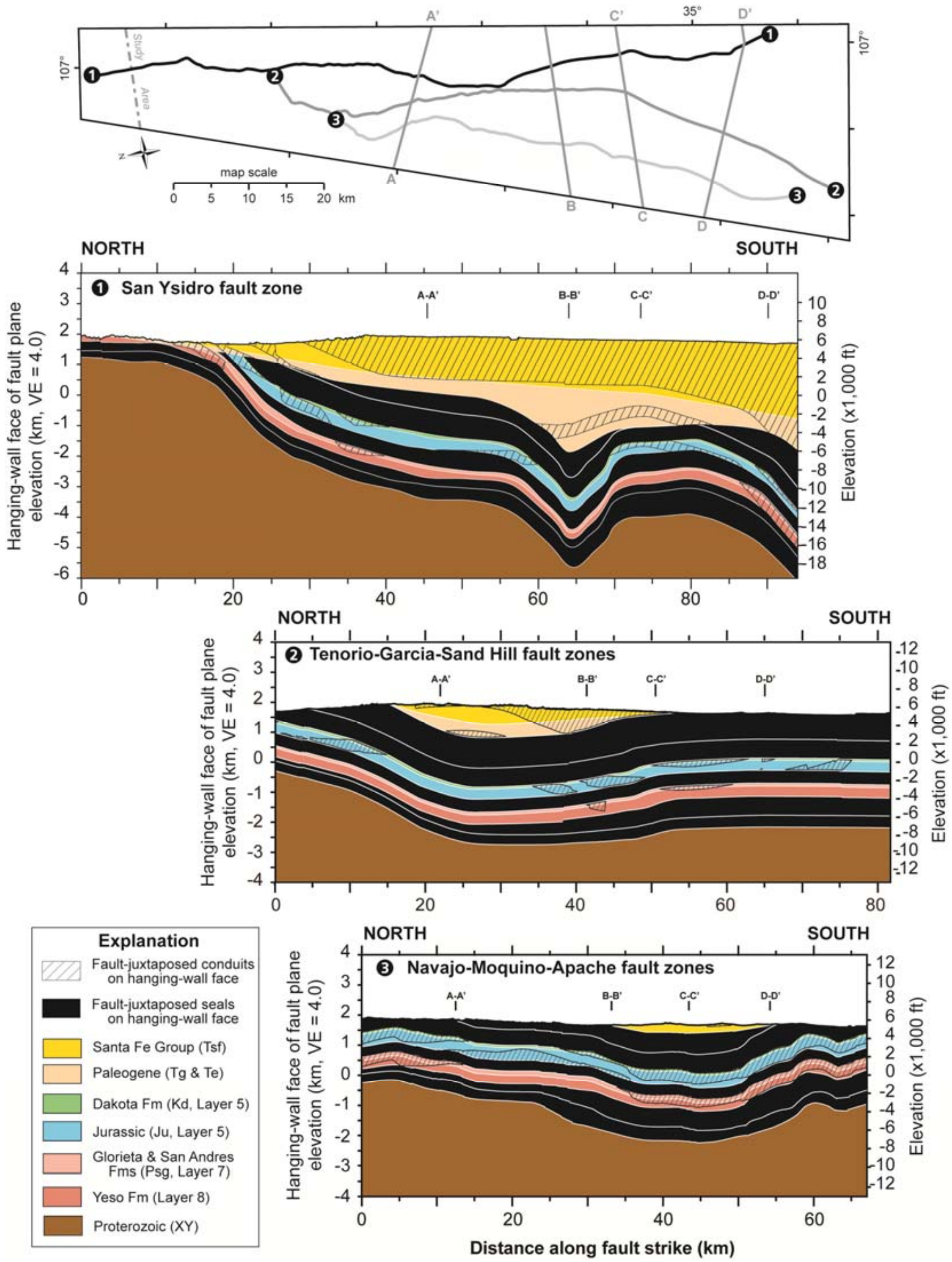

Figure 20. Simplified fault map and fault-trace cross sections, depicting the hanging-wall (basinward) face of the San Ysidro (1), Tenorio-Garcia-Sand Hill (2), and Navajo-Moquino-Apache (3) fault zones. Cross-cutting faults have been removed for clarity. Top: map showing mapped fault zones. Bottom: three cross sections illustrating seals (black) and conduits (hachured lines) for juxtaposed conduits and seals. Model layers are from Melis et al. (2011).

CONCLUSIONS

This study compiled available geologic data to produce a conceptual geologic framework to aid in the development of a groundwater-flow model by Melis et al. (2011). A summary of the regional stratigraphy was compiled from previously published studies and unpublished graduate theses. Data from 72 wells were interpreted and used to build two stratigraphic fences that depict regional variations in the pre-Cenozoic stratigraphy. Regional structure was examined through refinements to structure-contour maps of the top of the Precambrian (Broadhead et al., 2009), the base of the Upper Cretaceous Dakota Formation (Thaden and Zech, 1984), and the base of the Santa Fe Group (Grauch and Connell, *in press*). The structure-contour map of the Dakota Formation was extensively modified along the transition between the Colorado Plateau and Middle Rio Grande Basin (MRGB) using data from recent geologic mapping and interpretation of well data.

The character of the transition between the Colorado Plateau and MRGB may influence subsurface flow into the Rio Grande rift. The overall lack of springs on the Laguna bench may be a result of eastward tilting that does not expose Paleozoic units. The overall westward tilt of the rift-flanking Lucero uplift exposes upper Paleozoic units that are the sources of numerous springs. The potential influence of faults on groundwater movement was examined by mapping the juxtaposition of permeable and relatively impermeable stratigraphic units along three major fault zones that locally define the margin of the Colorado Plateau and Rio Grande rift: San Ysidro, Tenorio-Garcia-Sand Hill, and Navajo-Moquino-west Apache fault zones. Based on purely geometrical considerations, discontinuous conduits were mapped; suggesting variations in permeability (conduit windows) along faults that locally define the structural margin of the northwestern flank of the MRGB.

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APPENDIX

APPENDIX TABLE 1. SUMMARY OF STRATIGRAPHIC UNIT NAMES.

Strat. code	Unit
QTc	Volcanic rocks, undivided
QTs	Santa Fe Group, undivided
Te	Espinaso Fm & unit of Isleta well #2
Tg	Diamond Tail & Galisteo Fms, undivided
Ku	Upper Cretaceous, undivided
Kpc	Pictured Cliffs Sandstone
Kl	Lewis Shale, undivided
Kvch	Cliff House Sandstone
Kmf	Menefee Fm (Mesaverde Group)
Kpl	Point Lookout Sandstone (Mesaverde Group)
Kmu	upper Mancos Shale
Kg	Gallup Sandstone
Kml	lower Mancos Shale
Kd	Dakota Fm
Jm	Morrison Fm, undivided
Jt	Todilto Fm
Je	Entrada Sandstone
TRc	Chinle Group
TRa	Agua Sarca (Zarca) Formation
Psa	San Andres Limestone
Pg	Glorieta Sandstone
Py	Yeso Fm, undivided
Pym	Yeso Fm, Meseta Blanca Sandstone
Pa	Abo Fm
IPm	Madera Group, undivided
IPs	Sandia Fm & Arroyo Peñasco Group
XY	Proterozoic crystalline rocks, undivided

Note: Wells that record the top of the Permian have tops picked as Psa. Wells that recorded the top of the Pennsylvanian have tops picked as IPm.

APPENDIX TABLE 2. WELL DATA AND STRATIGRAPHIC PICKS.

	***Filon Exploration Federal #7**	***Conoco NMALCO #15-1**	***Sinclair Oil Richardson Federal #1**	***Merrion High Hopes #1**	***Diamond Shamrock Zambarmo Lake #41-18Y**	***Magnolia Petroleum Hutchison #1**	***Merrion #1 Federal Medio**
Code	*filonef7*	*conmalco15*	*sorichfed1*	*MOHiHo1*	*dszamlk1*	*magphut1*	*MOFeMed1*
Loc (S-T-R)	07.20N.02W	15.20N.12W	26.20N.13W	28.20N.05W	18.19N.02W	14.19N.03W	14.19N.03W
API (RG)	30-043-20200	30-031-20730	30-031-05361	30-031-20979	30-043-20803	30-043-05111	30-043-20031
Lat (°)	35.9766	35.9714	35.9420	35.9385	35.8838	35.8756	35.8728
Lon (°)	-107.0781	-108.1078	-108.1840	-107.3665	-107.0796	-107.1280	-107.1286
GSL (ft)	7,023	6,144	6,225	6,762	6,949	6,840	6,837
TD (ft)	6,415	4,620	3,520	6,050	5,815	9,684	5,310
Fm	Ꞧc	Je	Jm	Je	Ꞧc	XY	Je
Quad (7.5')	Mesa Portales	Nose Rock	Milk Lake	Ojo Encino	Mesa Portales	Johnson Trading Post	Wolf Stand
County	Sandoval	McKinley	McKinley	McKinley	Sandoval	Sandoval	Sandoval
Year completed	1976	1981	1958	1993	1986	1953	1990
<u>Strat. top (ft)</u>							
Ku	0	–	–	–	–	–	–
Kpc	685	–	–	–	–	–	–
Kl	784	–	–	0	0	0	0
Kvch	2,170	–	–	1,330	1,380	–	–
Kmf	2,238	0	0	1,408	1,446	–	1,126
Kpl	2,850	1,024	959	2,710	2,238	–	1,966
Kmu	3,057	1,204	1,086	2,845	2,363	2,114	2,108
Kg	4,266	2,300	1,972	3,510	3,582	–	2,792
Kml	4,315	2,385	–	4,670	3,634	–	3,164
Kd	5,035	3,204	3,088	4,870	4,368	4,208	4,216
Jm	5,709	3,328	3,221	4,975	4,694	4,444	4,436
Jt	6,135	4,372	–	5,850	5,568	5,190	5,238
Je	6,150	4,429	–	5,915	5,581	5,215	5,250
Ꞧc	6,283	–	–	–	5,760	5,548	–
Ꞧa	–	–	–	–	–	–	–
Psa	–	–	–	–	–	6358	–
Pg	–	–	–	–	–	–	–
Py	–	–	–	–	–	–	–
Pym	–	–	–	–	–	–	–
Pa	–	–	–	–	–	–	–
IPm	–	–	–	–	–	8454	–
IPs	–	–	–	–	–	–	–
XY	–	–	–	–	–	9,660	–
Source	3	1	1,3	2	3	3	2

Note: Wells not within study area denoted by asterisk (*). Upper Cretaceous stratigraphic picks, above the Menefee Fm, are listed, but not described in the text. GSL: ground-surface elevation (in feet). TD: total depth (in feet). *Sources:* [1]NM Oil Conservation Division; [2]NM Bureau of Geology Petroleum Information Center (e.g., Broadhead & Scholle, 2009), and Engler et al. (2001); [3]USGS Petroleum Information Center, Molenaar and Baird (1992), Sawyer and Minor (2006), and D.A. Sawyer (personal communication); [4]Black and Hiss (1974); [5]Reese (1971, 1978); [6]Lozinsky (1994), and Lozinsky and Tedford (1991); [7]Black (1982) and Maldonado et al. (1999); [8]Connell (2006); [9]Interra (2008); [10]Melis (2009); [11]Cather (1999); [12]Foster & Stipp (1961); and [13]Broadhead & Black (1989).

APPENDIX TABLE 2. WELL DATA AND STRATIGRAPHIC PICKS (CONTINUED).

	***Synergy Navajo Allotted #15-6**	***Merrion Boling Federal #5**	***Don C Wiley Federal Media #3**	***Merrion Miller Federal #722**	***Merrion Boling Federal #6**	***Filon Exploration Federal #30**	***Dome Petroleum Corp Tinian #26 Federal**
Code	*synajal15-6*	*BolingFed5*	*wileyfm3*	*MillerFed722*	*BolingFed6*	*filon301*	*domepf26*
Loc (S-T-R)	15.19N.05W	22.19N.03W	22.19N.03W	22.19N.03W	22.19N.03W	30.19N.02W	26.19N.05W
API (RG)	30-031-20510	30-043-20092	30-043-20033	30-043-20193	30-043-20149	30-043-20226	30-031-20491
Lat (°)	35.8726	35.8691	35.8690	35.8667	35.8656	35.8548	35.8438
Lon (°)	-107.3564	-107.1420	-107.1359	-107.1376	-107.1408	-107.0829	-107.3427
GSL (ft)	6,553	6,896	6,878	6,850	6,859	6,834	6,639
TD (ft)	5,392	5,450	5,343	5,285	5,245	5,376	8,936
Fm	Je	Je	Je	Je	Jt	Jm	XY
Quad (7.5')	Tinian	Wolf Stand	Wolf Stand	Wolf Stand	Wolf Stand	Headcut Reservoir	Tinian
County	McKinley	Sandoval	Sandoval	Sandoval	Sandoval	Sandoval	McKinley
Year completed	1977	1972	1969	1975	1974	1976	1977
Strat. top (ft)							
Kl	–	0	–	–	–	–	–
Kvch	–	480	–	–	445	–	–
Kmf	0	1,260	–	1,000	1,020	1,004	0
Kpl	1,956	2,018	1,987	–	2,025	1,839	1,898
Kmu	2,055	2,180	2,115	2,150	2,120	1,958	2,035
Kg	2,895	2,894	3,285	3,192	–	–	2,866
Kml	–	2,984	3,337	–	–	–	–
Kd	4,111	4,444	4,070	4,230	3,910	3,982	4,116
Jm	4,245	4,554	4,452	4,440	4,488	4,294	4,268
Jt	5,150	5,216	5,241	5,210	5,220	5,129	5,133
Je	5,160	5,342	5,317	5,290	–	5,158	5,230
₮c	–	–	–	–	–	–	5,416
₮a	–	–	–	–	–	–	–
Psa	–	–	–	–	–	–	–
Pg	–	–	–	–	–	–	6,450
Py	–	–	–	–	–	–	6,655
Pym	–	–	–	–	–	–	–
Pa	–	–	–	–	–	–	–
IPm	–	–	–	–	–	–	8,118
IPs	–	–	–	–	–	–	–
XY	–	–	–	–	–	–	8,892
Source	1	1	3	1	1	3	3

Note:
†faulted out

APPENDIX TABLE 2. WELL DATA AND STRATIGRAPHIC PICKS (CONTINUED).

	***El Paso Natural Gas Elliott State #1**	***Sun Oil Sandoval Federal #1**	***Prairie Dog Santa Fe #23**	***Mobil Jemez Pueblo #1**	***Kreatsch-mann & Stowe Arwood #14**	***South Hospah Unit #1-9**	***Santa Fe Railroad #42**
Code	*elpaels1*	*sunsanf1*	*PDSF23*	*mobjmzp1*	*stowan14*	*SHOSPU1-9*	*SFRR42*
Loc (S-T-R)	36.19N.02W	24.18N.03W	23.18N.08W	28.18N.01W	33.18N.03W	12.17N.09W	07.17N.08W
API (RG)	30-043-05102	30-043-20065	30-031-21058	30-043-20830	30-043-20041	30-031-20013	30-031-20745
Lat (°)	35.8357	35.7831	35.7782	35.7603	35.7530	35.7241	35.7187
Lon (°)	-106.9992	-107.1046	-107.6524	-106.9402	-107.1591	-107.7419	-107.7287
GSL (ft)	6,667	6,574	6,865	6,722	6,459	7,006	7,034
TD (ft)	8,225	8,750	3,407	5,984	3,382	3,890	4,029
Fm	XY	Mississippian	Jm	XY	Jm	Je	Je
Quad (7.5')	La Ventana?	Headcut Reservoir	Whitehorse	La Ventana	Wolf Stand	Hospah	Hospah
County	Sandoval	Sandoval	McKinley	Sandoval	Sandoval	McKinley	McKinley
Year completed	1953	1971	2004	1989	1967	1968	1982
Strat. top (ft)							
Kl	–	–	–	–	0	–	–
Kvch	–	–	–	–	571	–	–
Kmf	0	–	0	–	–	0	0
Kpl	–	1,102	1,046	–	967	315	582
Kmu	556	–	1,160	–	1,058	495	770
Kg	–	1,952	2,093	–	2,241	1,625	1,695
Kml	–	–	2,415	0	2,267	–	1,815
Kd	2,825	2,825	3,115	1,104	3,021	2,485	2,555
Jm	3,022	3,492	3,400	1,492	3,365	2,718	2,840
Jt	3,819	4,465	–	2,264	–	3,735	3,808
Je	3,925	4,572	–	2,368	–	3,788	3,890
TRc	4,090	4,748	–	2,496	–	–	–
TRa	–	5,870	–	3,645	–	–	–
Psa	5,394	–	–	–	–	–	–
Pg	–	5,960	–	3,748	–	–	–
Py	5,522	6,012	–	3,864	–	–	–
Pym	–	6,145	–	4,011	–	–	–
Pa	6,070	6,450	–	4,237	–	–	–
IPm	7049	7,635	–	5,241	–	–	–
IPs	–	8,540	–	5,690	–	–	–
XY	8,237	–	–	5,772	–	–	–
Source	3	3	1	3	3	1	1

APPENDIX TABLE 2. WELL DATA AND STRATIGRAPHIC PICKS (CONTINUED).

	***Eastern Petroleum Tenneco Fullop #1**	***Shell Oil Wright #41-26**	***Refiners Petroleum Cabezon #1**	**Enexco Shirl #2**	**Merrion Boomer Sooner #1**	**Santa Fe Railroad #11**	**Hughes & Hughes Fed Tract 17**
Code	*eptenful1*	*shwrit41*	*reficab1*	*enxshrl2*	*moboso1*	*SFRR11*	*hughhuf1*
Loc (S-T-R)	19.17N.08W	26.17N.03W	29.17N.04W	10.16N.02W	21.16N.09W	29.16N.06W	25.16N.05W
API (RG)	30-031-20230	30-043-05026	30-043-20069	30-043-20666	30-031-20960	30-031-20405	30-031-05516
Lat (°)	35.6835	35.6808	35.6767	35.6313	35.6066	35.5904	35.5900
Lon (°)	-107.7328	-107.1143	-107.2799	-107.0424	-107.7948	-107.4923	-107.3194
GSL (ft)	7,010	6,339	6,435	6,214	7,099	6,124	6,770
TD (ft)	3,035	6,952	4,055	7,070	3,254	3,062	2,612
Fm	Jm	XY	ꞦRc	XY	Je	Je	Jm
Quad (7.5')	Hospah	San Luis	Canada Calladita	San Luis	Mesa de los Toros	Mesa Cortada	Cerro Parida
County	McKinley	Sandoval	Sandoval	Sandoval	McKinley	McKinley	Sandoval
Year completed	1972	1961	1971	1983	1991	1974	1966
<u>Strat. top (ft)</u>							
Kmf	0	0	0	–	–	–	0
Kpl	532	–	590	–	0	–	190
Kmu	786	180	778	0	160	–	382
Kg	1,850	972	–	565	965	815	1,428
Kml	–	–	–	628	–	1,623	1,885
Kd	–	2,000	2,838	1,414	1,795	1,833	2,306
Jm	3,015	2,390	2,942	1,756	2,010	2,000	2,612
Jt	–	3,355	3,850	2,544	3,092	2,960	–
Je	–	3,468	3,870	2,671	3,110	3,045	–
ꞦRc	–	3,554	4,002	2,828	–	–	–
ꞦRa	–	–	–	–	–	–	–
Psa	–	4,590	–	4,124	–	–	–
Pg	–	–	–	4,130	–	–	–
Py	–	–	–	4,149	–	–	–
Pym	–	–	–	4,210	–	–	–
Pa	–	–	–	4,464	–	–	–
IPm	–	6,030	–	4970	–	–	–
IPs	–	–	–	6,701	–	–	–
XY	–	6,930	–	6,840	–	–	–
Source	1	3	1	3	1	1	3

APPENDIX TABLE 2. WELL DATA AND STRATIGRAPHIC PICKS (CONTINUED).

	Thomas Drought #1	**Houston Oil Booth Draught #2**	**Shar-Alan Fernandez #7**	**Avila Oil Odlum Federal #1**	**Merrion Sarcio #1**	**Damson Oil Fernandez #13**	**RA Crane Jr. Crane Fernandez #1**
Code	*ThomDro1*	*hombdro2*	*shalfern7*	*avilodl1*	*MOSarcio1*	*dofern13*	*CranFernz1*
Loc (S-T-R)	04.15N.06W	01.15N.04W	01.15N.08W	15.15N.01W	16.15N.06W	13.15N.08W	33.15N.08W
API (RG)	30-031-20542	30-043-20262	30-031-20350	30-043-05015	30-031-20984	30-031-20530	30-031-20059
Lat (°)	35.5653	35.5631	35.5606	35.5361	35.5323	35.5276	35.4916
Lon (°)	-107.4691	-107.2041	-107.6393	-106.9226	-107.4797	-107.6402	-107.6838
GSL (ft)	6,610	6,195	6,687	5,961	6,736	6,739	6,889
TD (ft)	3,060	6,920	2,750	5,394	3,552	2,592	2,600
Fm	Je	XY	Jm	XY	Je	Jm	Jm(?)
Quad (7.5')	Mesa Cortada	Guadalupe	Piedra de la Aguila	Ojito Spring	Mesa Cortada	Piedra de la Aguila	San Lucas Dam
County	McKinley	Sandoval	McKinley	Sandoval	McKinley	McKinley	McKinley
Year completed	1978	1977	1971	1953	1996	1977	1967
Strat. top (ft)							
Kl	–	–	–	–	–	–	–
Kvch	0	–	–	–	–	–	–
Kmf	218	–	–	–	–	0	–
Kpl	470	–	–	–	0	810	–
Kmu	*faulted*	0	0	–	75	1,055	–
Kg	805	455	1,646	–	1,152	1,276	1,262
Kml	900	568	1,730	–	1,265	–	–
Kd	1,634	1,345	2,440	–	1,985	2,259	2,255
Jm	2,030	1,492	2,730	0	2,306	2,550	2,410
Jt	2,954	2,504	–	730	3,260	–	–
Je	3,060	2,586	–	880	3,343	–	–
ŦRc	–	2,745	–	1,060	–	–	–
ŦRa	–	4,036	–	–	–	–	–
Psa	–	4,102	–	2,220	–	–	–
Pg	–	4,108	–	2,310	–	–	–
Py	–	4,177	–	2,950	–	–	–
Pym	–	4,618	–	3,660	–	–	–
Pa	–	4,882	–	3,730	–	–	–
IPm	–	5,447	–	4,545	–	–	–
IPs	–	6,765	–	5,326	–	–	–
XY	–	6,861	–	5,353	–	–	–
Source	1	3	1	3	1	1	3

APPENDIX TABLE 2. WELL DATA AND STRATIGRAPHIC PICKS (CONTINUED).

	Superior San Mateo Govt. #1-14	**Humble Oil & Refining Co. #1 Santa Fe B**	**Conoco L-Bar Cattle #1 Evans**	**Caprock P&S L-Bar Ranch #1**	**Texaco Howard-Major #1**	**RG-88934 POD2 well #6**	**RG-88934 POD1 well #5**
Code	*SMG1-14*	*humsfpb1*	*conlbar1*	*caplbar1*	*texhmaj1*	*RG88934-6*	*RG88934-5*
Loc (S-T-R)	14.14N.08W	20.14N.01W	02.13N.04W	02.13N.04W	10.13N.03W	11.12N.01W	10.12N.01W
API (RG)	30-031-05030	30-043-05011	30-043-05010	30-043-20948	30-043-07001	(88934 POD2)	(88934 POD1)
Lat (°)	35.4414	35.4342	35.3873	35.3831	35.3684	35.2855	35.2836
Lon (°)	-107.6608	-106.9713	-107.2193	-107.2188	-107.1488	-106.8852	-106.9264
GSL (ft)	7,165	6,149	6,570	6,564	6,243	5,850	5,720
TD (ft)	6,253	6,016	6,220	6,180	6,387	3,850	6,460
Fm	XY	XY	XY	XY	XY	Psa	XY
Quad (7.5')	San Lucas Dam	Sky Village NW	Cerro Tinaja	Cerro Tinaja	La Gotera	San Felipe Mesa	San Felipe Mesa
County	McKinley	Sandoval	Sandoval	Sandoval	Sandoval	Sandoval	Sandoval
Year completed	1954	1954	1935	1999	1964	2008	2008
<u>Strat. top (ft)</u>							
Kpl	–	–	–	–	–	0	–
Kmu	–	–	–	–	–	*faulted*	–
Kg	–	–	–	–	–	*faulted*	502?
Kml	–	–	0	0	0	*faulted*	641?
Kd	0	0	258	82	120	*faulted*	470
Jm	1,220	327	290	349	170	1,385	560
Jt	2,149	1,150	1,140	1,172	1,154	1,525	1,448
Je	2,205	1,244	1,250	1,245	1,170	1,720	1,547
₸c	2,502	1,420	1,330	1,405	1,472	3,205	1,810
₸a	2,749	2,730	–	2,967	–	3,365	3,265
Psa	–	3,075	2,763	3,062	–	3,550	3,430
Pg	3,950	3,172	2,895	3,178	2,850	–	3,565
Py	4,022	3,305	–	3,297	3,074	–	3,695
Pym	–	3,791	–	3,777	–	–	4,060
Pa	–	4,024	3,630	4,001	4,400	–	4,220
IPm	5,568	4,930	4,815	5,373	5,075	–	5,130
IPs	–	5,875	5,948	5,940	6,080	–	6,220
XY	6,205	6,008	6,134	6,129	6,275	–	6,350
Source	10	3,11	3	3	3	9	9

APPENDIX TABLE 2. WELL DATA AND STRATIGRAPHIC PICKS (CONTINUED).

	Davis Pet. Tamara #1-Y	**Shell Santa Fe Pacific #1**	**Shell Santa Fe Pacific #3**	**Shell West Mesa Federal #1-24**	**Westland Devel. UTEX Oil #1**	**XTO Westland #15-1**	**XTO Barbara Page #211**
Code	*davtam1y*	*shsfp1*	*shsfp3*	*shelwmf1*	*utexwes1*	*xtowlan1*	*burwes1y*
Loc (S-T-R)	03.13N.02E	18.13N.03E	28.13N.01E	24.11N.01E	01.10N.01E	15.10N.01W	21.10N.01E
API (RG)	30-043-20934	30-043-20094	30-043-20211	30-001-20004	30-001-20005	30-001-20012	30-001-20007
Lat (°)	35.3801	35.3534	35.3238	35.1704	35.1191	35.0900	35.0749
Lon (°)	-106.7165	-106.6696	-106.8411	-106.7841	-106.7840	-106.9245	-106.8491
GSL (ft)	6,113	5,733	6,281	5,778	5,752	5,367	5,940
TD (ft)	8,732	11,045	10,276	19,350	16,665	6,632	7,800
Fm	₮c	XY	₮c	Jm	Kmu	Jm	₮c
Quad (7.5')	Bernalillo NW	Loma Machette	Arroyo de las Calabacillas	The Volcanoes	La Mesita Negra SE	La Mesita Negra	La Mesita Negra SE
County	Sandoval	Sandoval	Sandoval	Bernalillo	Bernalillo	Bernalillo	Bernalillo
Year completed	1996	1972	1976	1982	1984	2005	1997
<u>Strat. top (ft)</u>							
QTs	0	0	0	0	0	0	0
Te	3,760	–	3,260	8,540	–	–	2,500
Tg	5,350	2,970	3,996	15,708	–	–	4,814
Ku	–	–	–	–	–	–	–
Kpc	–	–	–	–	–	–	–
Kl	–	–	–	–	–	–	–
Kvch	–	–	–	–	–	–	–
Kmf	6,490	3,644	4,068	16,300	–	3,539	5,201
Kpl	–	4,378	6,138	16,817	–	4,566	5,213
Kmu	–	4,520	–	16,880	–	4,646	–
Kg	–	–	–	18,082	–	5,184	6,615
Kml	–	–	–	18,330	–	5,314	6,838
Kd	8,170	6,542	8,731	18,785	–	6,149	6,907
Jm	8,330	6,907	9,078	19,090	–	6,458	7,180
Jt	8470†	7,452	10,017	–	–	–	7,492
Je	8,555	7,528	10,140	–	–	–	7,578
₮c	8,680	7,727	10,164	–	–	–	7,697
₮a	–	8,738	–	–	–	–	–
Psa	–	8,875	–	–	–	–	–
Pg	–	8,900	–	–	–	–	–
Py	–	8,992	–	–	–	–	–
Pym	–	9,378	–	–	–	–	–
Pa	–	9,632	–	–	–	–	–
₱m	–	10,376	–	–	–	–	–
₱s	–	–	–	–	–	–	–
XY	–	10,995	–	–	–	–	–
Source	2,8, †8480-8540 ft	3,4	2,6	3,9	3	3	2

APPENDIX TABLE 2. WELL DATA AND STRATIGRAPHIC PICKS (CONTINUED).

	XTO Armijo Trust #27-1	**Shell Laguna Wilson Trust #1**	**Shell #1 Isleta Central**	**Humble Santa Fe Pacific #1**	**Shell Oil #2 Santa Fe**
Code	*xtoarmt1*	*shlagwt1*	*shislc1*	*humsfp1*	*shellsf2*
Loc (S-T-R)	27.10N.01W	08.09N.01W	07.07N.02E	18.06N.01W	29.06N.01W
API (RG)	30-001-20010	30-001-20001	30-061-20008	30-061-05006	30-061-20004
Lat (°)	35.0610	35.0241	34.8539	34.7409	34.7147
Lon (°)	-106.9243	-106.9676	-106.7782	-106.9764	-106.9718
GSL (ft)	5,342	5,415	5,066	5,092	5,216
TD (ft)	5,482	11,115	16,346	12,691	14,305
Fm	Jm	XY	Je	Kmf	Ʈc
Quad (7.5')	La Mesita Negra	La Mesita Negra	Dalies	Belen NW	Belen NW
County	Bernalillo	Bernalillo	Valencia	Valencia	Valencia
Year completed	2005	1972	1975	1953	1974
Strat. top (ft)					
QTs	0	0	0	0	0
Te	–	–	8,789	4,902	4,801
Tg	–	–	10,551	7,100	7,609
Ku	–	–	–	–	8,249
Kpc	–	–	–	–	–
Kl	–	–	–	–	–
Kvch	–	–	–	–	–
Kmf	2,570	10	12,110	8,501	10,850
Kpl	3,572	1,480	–	–	–
Kmu	3,634	–	–	–	–
Kg	4,170	2,652	13,090	–	12,980
Kml	4,306	2,779	13,265	–	13,010
Kd	5,126	3,678	–	–	13,787
Jm	5,450	3,855	–	–	*pinched out*
Jt	–	4,478	–	–	13,928
Je	–	4,590	–	–	13,954
Ʈc	–	4,719	13,508 (13,808?)	–	14,058
Ʈa	–	–	*faulted?*	–	–
Psa	–	6,300	13,890	–	–
Pg	–	6,618	14,040	–	–
Py	–	6,830	14,275	–	–
Pym	–	7,355	14,795	–	–
Pa	–	7,605	14,975	–	–
IPm	–	8,461	15,960?	–	–
IPs	–	10,500	–	–	–
XY	–	11,102	–	–	–
Source	3	3	7	6	2,3

APPENDIX TABLE 2. WELL DATA AND STRATIGRAPHIC PICKS (CONTINUED).

	Austra-Tex Rio Puerco Federal #1-7	**Austra-Tex Exxon-Mineral Fee #1**	**Grace Michael Sandy #1**	**King Wilson Heirs Unit #1**	**NMex & Arizona Land Co #2A**	**Gore & Lipscomb Federal B1**	**Williams & Gore NM Land & Cattle #1**
Code	*austxrp1*	*austxex1*	*grasand1*	*kingwil1*	*hinmazl1*	*gorlipb1*	*wilgorn1*
Loc (S-T-R)	07.12N.02W	21.12N.03W	21.12N.03W	14.07N.03W	27.07N.04W	26.07N.04W	27.07N.04W
API (RG)	30-043-20818	30-006-20007	30-043-20102	30-061-05026	30-061-07041	30-061-05021	30-061-05019
Lat (°)	35.2833	35.2584	35.2491	34.8320	34.8070	34.8052	34.8026
Lon (°)	-107.0839	-107.2220	-107.1552	-107.1160	-107.2500	-107.2316	-107.2531
GSL (ft)	5,956	6,651	6,027	5,891	6,061	6,042	5,958
TD (ft)	6,324	5,723	1,500	3,993	3,676	3,676	3,660
Fm	XY	IPm	Ŧc	XY	Pennsylvanian	Pennsylvanian	IPm
Quad (7.5')	Puerco Dam	La Gotera	Arch Mesa	South Garcia SE	Cerro Verde	White Ridge	Cerro Verde
County	Sandoval	Sandoval	Sandoval	Valencia	Cibola	Cibola	Cibola
Year completed	1973	1987	1973	1958	1959	1958	1957
<u>Strat. top (ft)</u>							
Km	0	–	–	–	–	–	–
Kd	–	150	–	–	–	–	–
Jm	330	260	0	–	–	–	–
Jt	1,250	1,220	650	–	–	–	–
Je	1,315	1,280	744	–	–	–	–
Ŧc	1,405	1,420	864	–	–	–	–
Ŧa	3,083	2,870	–	–	–	–	–
Psa	3,220	2,912	–	–	0	0	0
Pg	–	3,062	–	–	–	–	270
Py	3,590	3,160	–	0	395	398	430
Pym	–	3,595	–	–	–	–	–
Pa	4,320	3,855	–	1,076	1,435	1,435	1,435
IPm	5,168	5,015	–	1,902	2,645	2,645	2,700
IPs	6,140	–	–	3,614	–	–	–
XY	6,235	–	–	3,946	–	–	–
Source	3	3	3	2,5	3	3, 13	3

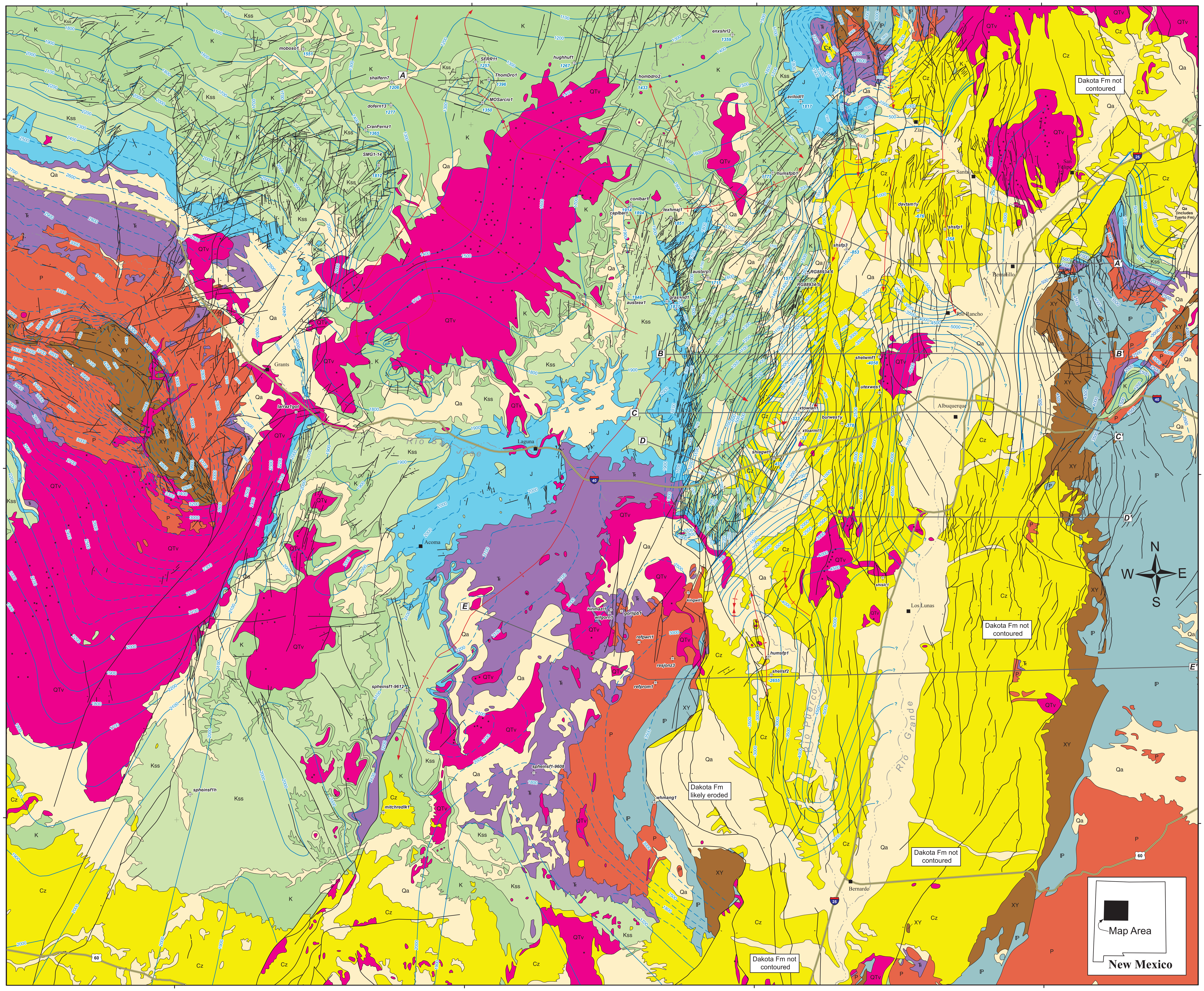
APPENDIX TABLE 2. WELL DATA AND STRATIGRAPHIC PICKS (CONTINUED).

	Refiners Petroleum #1 White Ridge	**Reese & Jones NZ #3**	**Refiners Petroleum Romero #1**	***Tiger Oil 1 State #8**
Code	*refpwri1*	*resjonz3*	*refprom1*	*tiostate8*
Loc (S-T-R)	07.06N.03W	22.06N.03W	32.06N.03W	08.04N.17W
API (RG)	30-061-20003	30-061-20014	30-061-20001	30-006-20002
Lat (°)	34.7607	34.7376	34.7030	34.5885
Lon (°)	-107.2012	-107.1427	-107.1721	-108.6340
GSL (ft)	6,749	5,956	6,283	6,781
TD (ft)	4,298	2,725	3,028	4,491
Fm	XY	XY	XY	IPs(?)
Quad (7.5')	White Ridge	Mesa Gallina	Mesa Gallina	Fence Lake SW
County	Valencia	Valencia	Valencia	Cibola
Year completed	1971	1980	1971	1978
Strat. top (ft)				
Km	–	–	–	0
Kd	–	–	–	805
Jm	–	–	–	–
Jt	–	–	–	–
Je	–	–	–	–
ꞦRc	–	–	–	870
ꞦRa	–	–	–	–
Psa	0	–	–	2167
Pg	–	–	–	2522
Py	370	–	–	2728
Pym	–	–	–	–
Pa	1,715	0	0	4008
IPm	2,465	–	610	–
IPs	3,825	2,260	2,450	4338
XY	4,268	2,407	2,898	–
Source	5	3,5	5	2, 13

APPENDIX TABLE 2. WELL DATA AND STRATIGRAPHIC PICKS (CONTINUED).

	Spanel & Heinze #1H Santa Fe	**Spanel & Heinze #1 1-9612 Santa Fe**	**Spanel & Heinze #1 1-9608 Santa Fe**	**White & Mangels #1 State**	**Mitchell #1 Red Lake**	***Huckle Berry #1 Federal**	**Larrazolo #1 Gottlieb**
Code	*speinsf1h*	*speinsf1-9612*	*speinsf1-9608*	*whmang1*	*mitchredlk1*	*huckber1*	*larraz1got*
Loc (S-T-R)	27.04N.11W	05.05N.07W	17.04N.05W	32.04N.03W	02.03N.08W	11.02N.16W	21.10N.09W
API (RG)	not available	not available	not available	not available	not available	not available	not available
Lat (°)	34.5380	34.6900	34.5740	34.5320	34.5140	34.4140	35.0870
Lon (°)	-107.9770	-107.6040	-107.3820	-107.1730	-107.6430	-108.4890	-107.8000
GSL (ft)	7,401	7,486	6,057	6,200	6,600	7,109	6,392
TD (ft)	5,397	4,992	4,746	201	4,012	5,642	4,913
Fm	XY	XY	XY	XY	XY	XY	XY
Quad (7.5')	Bonine Canyon	Broom Mountain	Field Ranch	Mesa Sarca	Wiley Mesa	Mariano Springs	Grants SE
County	Catron	Cibola	Socorro	Socorro	Socorro	Catron	Cibola
Year completed	1959	1959	1959	1947	1925	1956	1954
<u>Strat. top (ft)</u>							
QTv	–	–	–	–	–	–	0
Tg	–	–	–	–	–	0	–
K	–	0	–	–	–	–	–
XY	2,031	4,975	4,746	172	3,986	5,520	4,756
Source	12, 13	12, 13	12, 13	12, 13	12, 13	12, 13	12, 13

OFR-539 GENERALIZED GEOLOGIC MAP AND STRUCTURE CONTOURS OF THE BASE OF THE DAKOTA FM PLATE 1



EXPLANATION

shsfp1 -100 Well (elevation of base of Dakota Fm, m)

River

A —— A' Cross section

Fault, ball on downthrown side; cross-cutting relationships not shown

Anticline

Syncline

—1000- - Elevation of base of Dakota Fm (m); dashed line denotes areas removed by erosion.

—0— Elevation of base of Dakota Fm (m); Index contour (0 m)

QTv Cenozoic volcanic rocks, undivided

XY Proterozoic crystalline rocks, undivided

Qa Quaternary alluvium, undivided

Cz Cenozoic, undivided

K Cretaceous, undivided

Kss *Cretaceous sandstone*

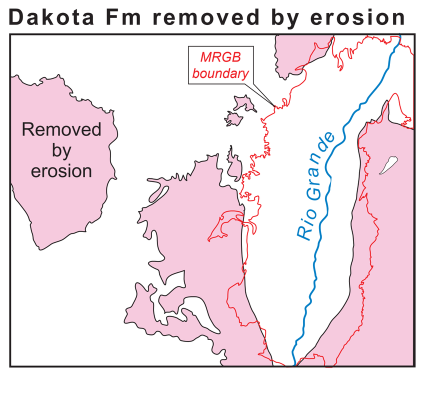
J Jurassic, undivided

₮ Triassic, undivided

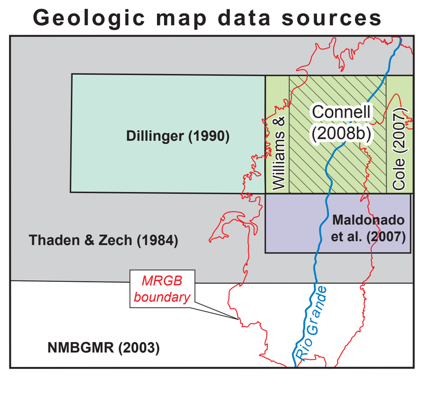
P Permian, undivided

ℙ Pennsylvanian & Mississippian, undiv.

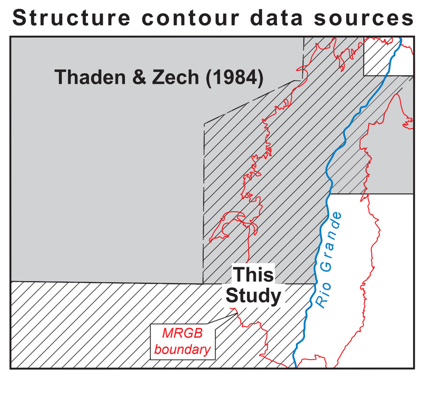
Dakota Fm removed by erosion



Geologic map data sources



Structure contour data sources



Scale

0 10 20 30 km

1:250,000

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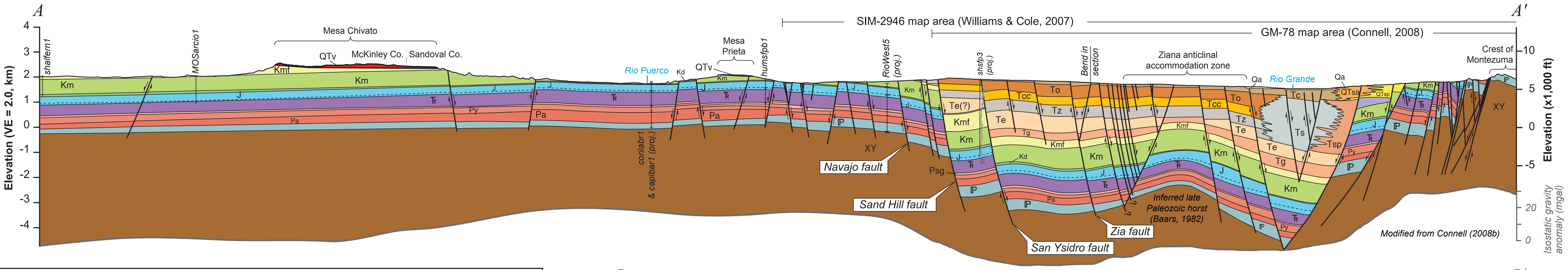
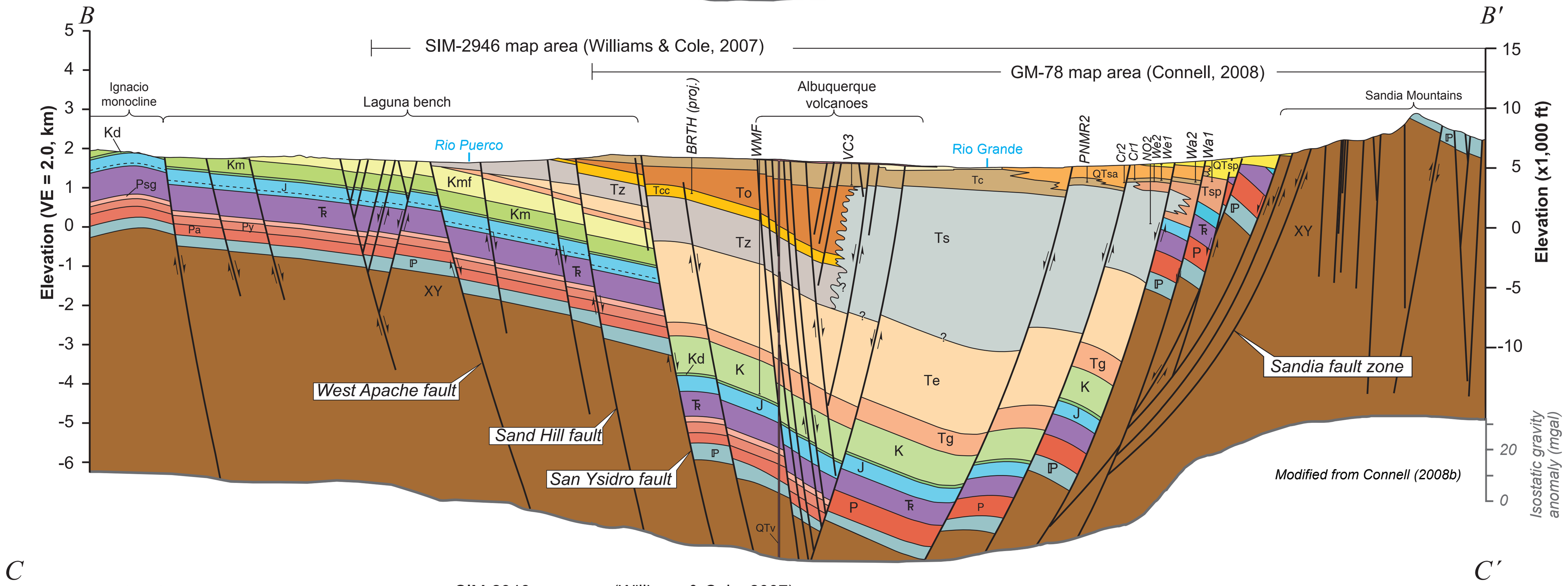
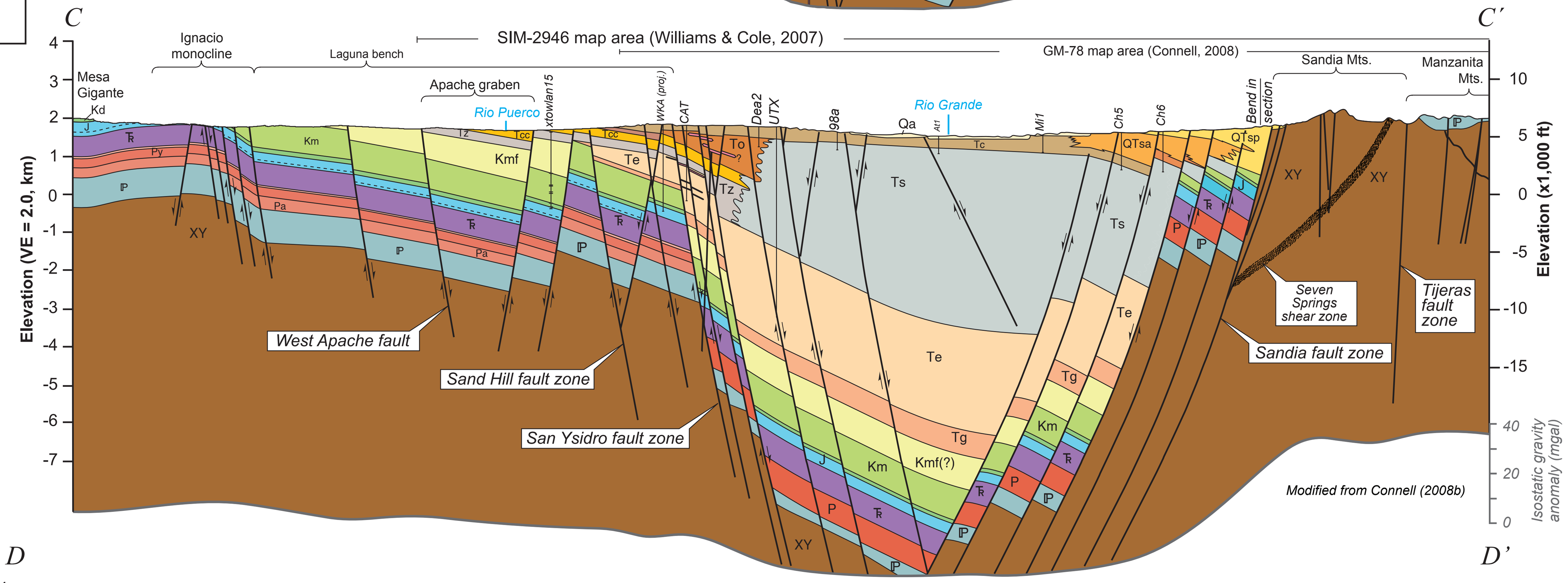
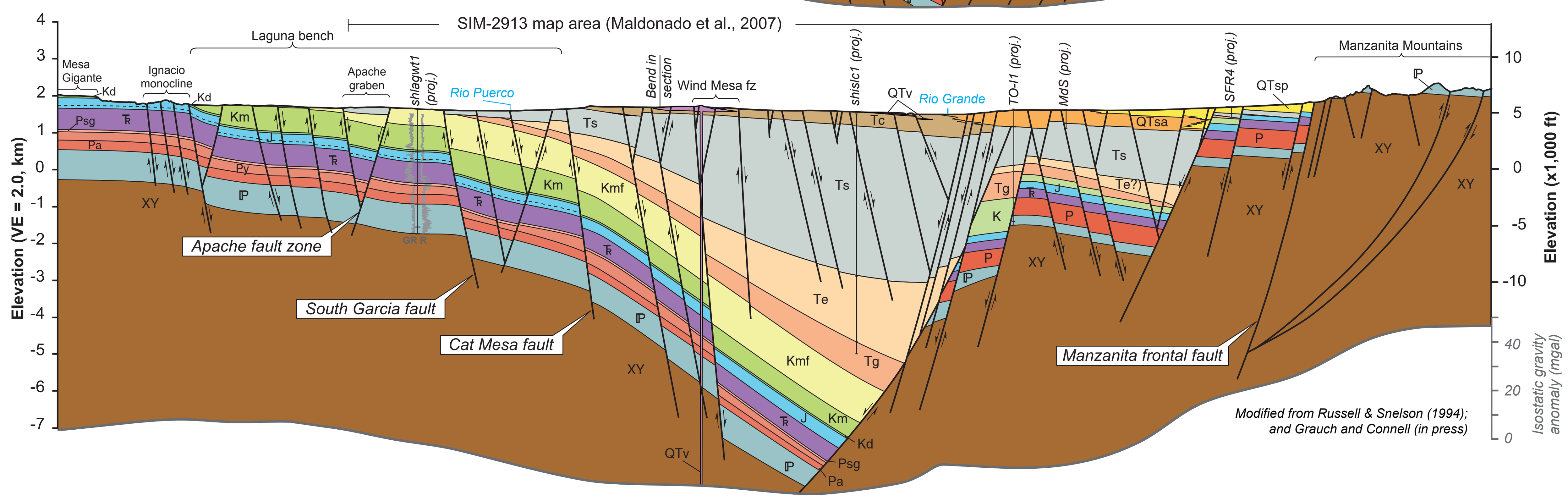
GEOLOGIC CROSS SECTIONS

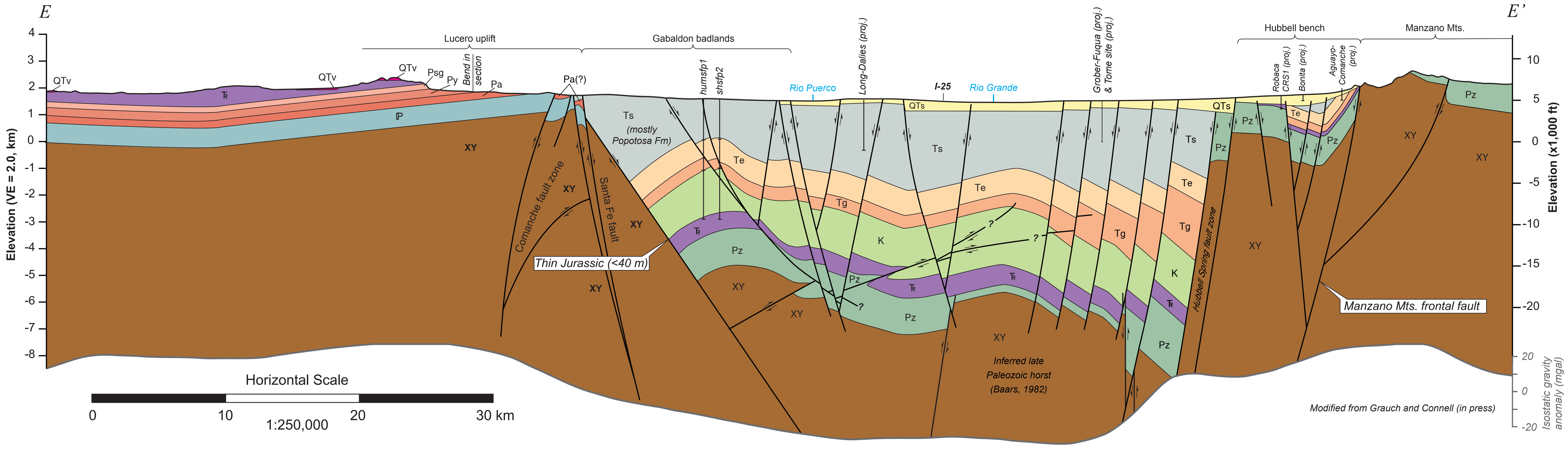
PLATE 2











EXPLANATION

- QTv — **Cenozoic volcanic rocks, undivided**
- Qa — Quaternary alluvium, undivided
- QTs — Upper Santa Fe Group
  - QTsp / QTsa — *Sierra Ladrones Fm (QTsp = piedmont; QTsa = axial-fluvial)*
  - Tc — *Ceja Fm, undivided*
- Ts — Lower & Middle Santa Fe Group
  - To — *Arroyo Ojito Fm, undivided*
  - Tcc — *Cerro Conejo Fm, undivided*
  - Tz — *Zia Fm, undivided*
- Te — Espinaso Fm & unit of Isleta well #2
- Tg — Diamond Tail & Galisteo Fms
- Mz — **Mesozoic sedimentary rocks, undivided**
  - K — Cretaceous, undivided
    - Kmf — *Menefee Fm & Mesaverde Group, undiv.*
    - Km — *Mancos Shale, undiv.*
    - Kd — *Dakota Fm*
  - J, Jm, Jet — Jurassic, undivided (Jm = Morrison Fm; Jet = Entrada & Todilto Fms)
  - ℞ — Triassic, undivided (mostly Chinle Group)
- Pz — **Paleozoic sedimentary rocks, undivided**
  - P — *Permian rocks, undivided*
    - Psg — *Glorieta Sandstone & San Andres Limestone, undivided*
    - Py — *Yeso Fm*
    - Pa — *Abo Fm*
  - IP — Pennsylvanian & Mississippian, undiv. (Sandia Fm, Madera & Arroyo Peñasco Groups)
- XY — **Proterozoic crystalline rocks, undivided**

- fault; arrows denote relative movement
- geologic contact
- Cretaceous-Jurassic boundary
- shlagwt1 (GR, R) — well; geophysical logs include natural gamma ray (GR) and resistivity (R)
- 20 / 0 / -20 — profile of isostatic residual gravity anomaly (mgal) at base of cross sections (data from Kucks et al., 2001); vertical position does not denote compensation depth.

INDEX MAP

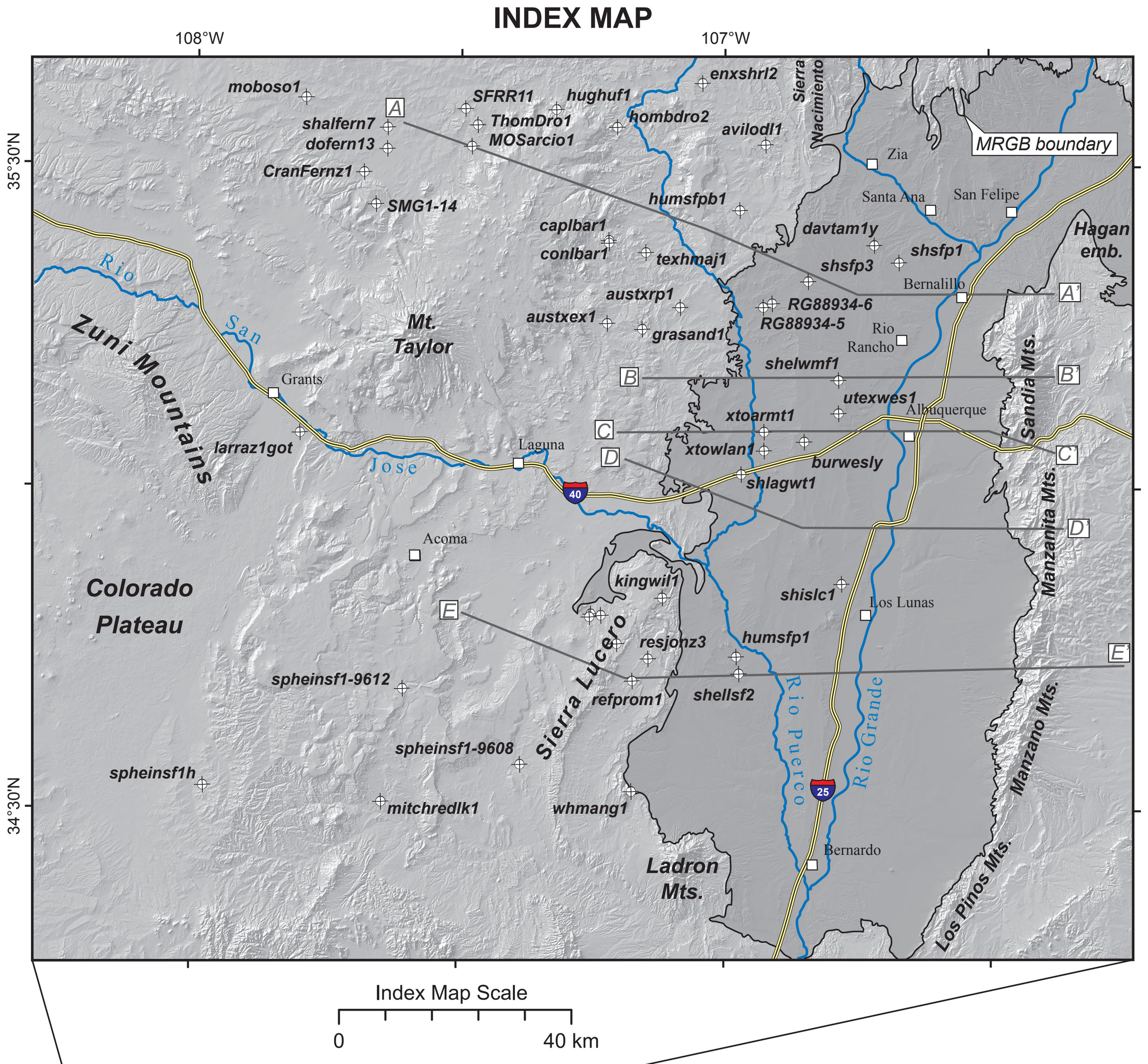


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Plate 2
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