The Oil and Natural Gas Potential Of Sandoval County, New Mexico and its Relationship to Groundwater, With a Discussion of Modern Oil Drilling Methods and Possibilities for Aquifer Contamination

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TABLE OF CONTENTS

Section	**Page**

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EXECUTIVE SUMMARY

The primary purpose of this report is to present an independent evaluation of the oil and natural gas potential of Sandoval County (see Figure 1 for the location of the county within New Mexico). The need for this evaluation was triggered by an application to drill an oil exploration well in the Rio Rancho area that would have targeted the Upper Cretaceous Mancos Shale. Although oil and natural gas have been produced from the northwestern part of the county since the 1950's, the proposed well, if successful, would result in the first oil production from the southern part of the county and more specifically, from the Albuquerque Basin. In Sandoval County, the Albuquerque Basin is relatively deep where present in the county and contains up to 4,000 ft of Tertiary sediments. Sandstones in the upper parts of the Tertiary section form aquifers that supply much of the drinking water to the urban communities that cover the Rio Rancho and Bernalillo areas. The quality of the water decreases substantially in the middle and lower parts of the Tertiary section. Concerns have arisen as to the effect of oil drilling and production activities on groundwater supplies. These concerns led to two additional purposes for this report, one of which was to describe the occurrence and quality of groundwater throughout the county. The other additional purpose is to provide an overview of modern oil-well drilling and production technologies and to provide a review of the possible effects of these technologies on aquifers within the county.

Sandoval County is located in northwestern New Mexico (Figure 1). Several major geologic elements are present within the county. The most visibly obvious of these elements visible are the three mountain ranges (Figure 2). The Sierra Nacimiento in the north-central part of the county separates the San Juan Basin on the west from the Jemez volcanic field on the east. It is the only one of the three mountain ranges that is entirely present within the county. The San Pedro Mountains are present just north of the Sierra Nacimiento, but the majority of this mountain range is present to the east in southernmost Rio Arriba County. The Sierra Nacimiento and San Pedro Mountains form a geologic unit in which Precambrian basement rocks are exposed along the higher parts of the mountains. Pennsylvanian and Permian sedimentary rocks are exposed along the eastern slopes of the mountains, having been eroded from the higher areas. Steep faults separate the mountain ranges from the San Juan Basin to the west. The mountain ranges have zero to very low oil and natural gas potential. Cretaceous sedimentary rocks, including the Mancos Shale, have produced the vast majority of oil and natural gas in the northwestern part of the county and have been eroded from the mountain ranges. The Jurassic Entrada Sandstone, which has produced small volumes of oil from the San Juan Basin, is present on the flanks of the mountain ranges in some places but any traps have been breached by erosion so that Entrada potential is low where it has been preserved on the mountain flanks. The Pennsylvanian and Permian strata exposed extensively on the eastern flanks of the mountains have poor petroleum source-rock potential, rendering the oil and gas potential of these strata low.

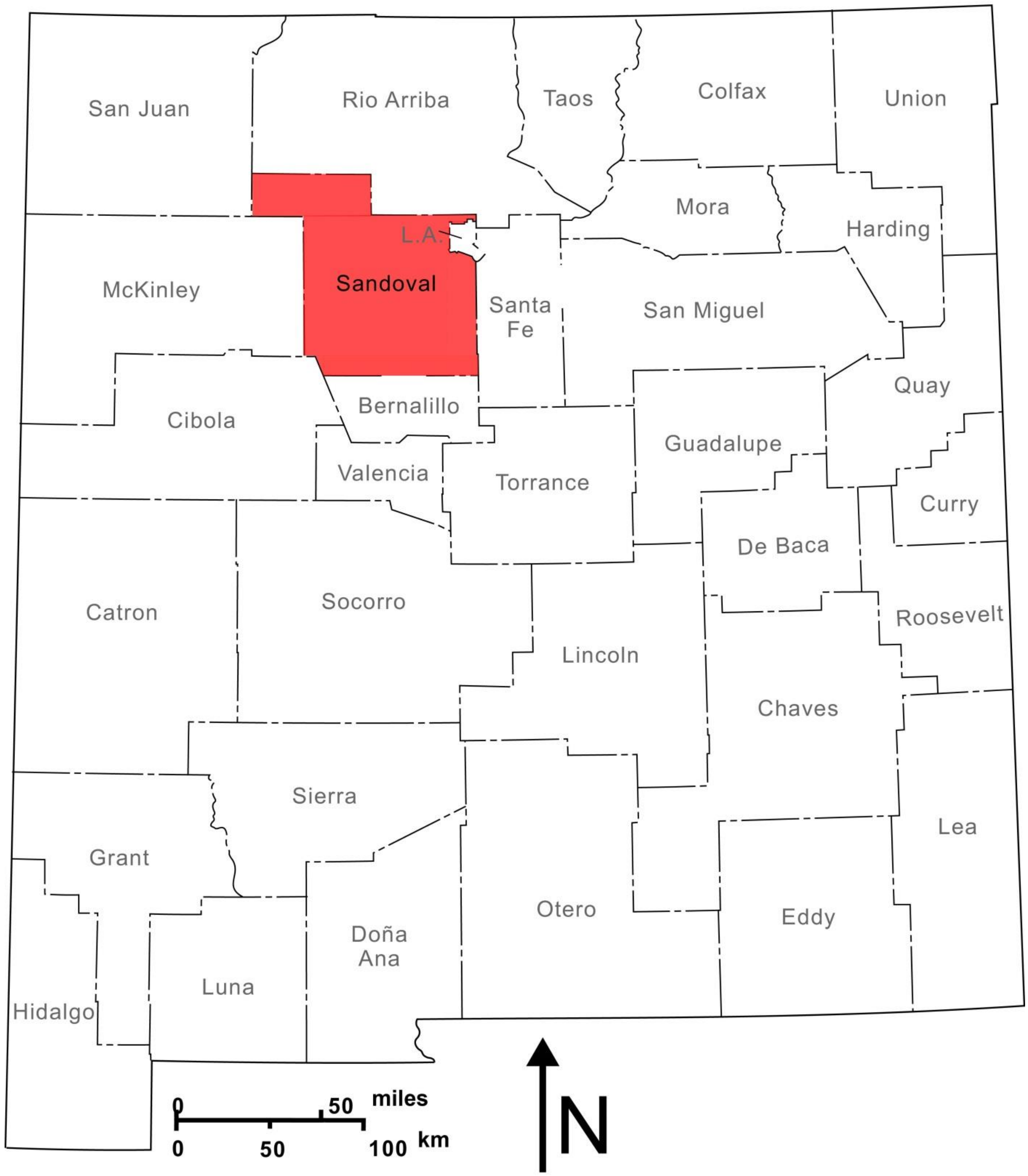


Figure 1. Location of Sandoval County within New Mexico.

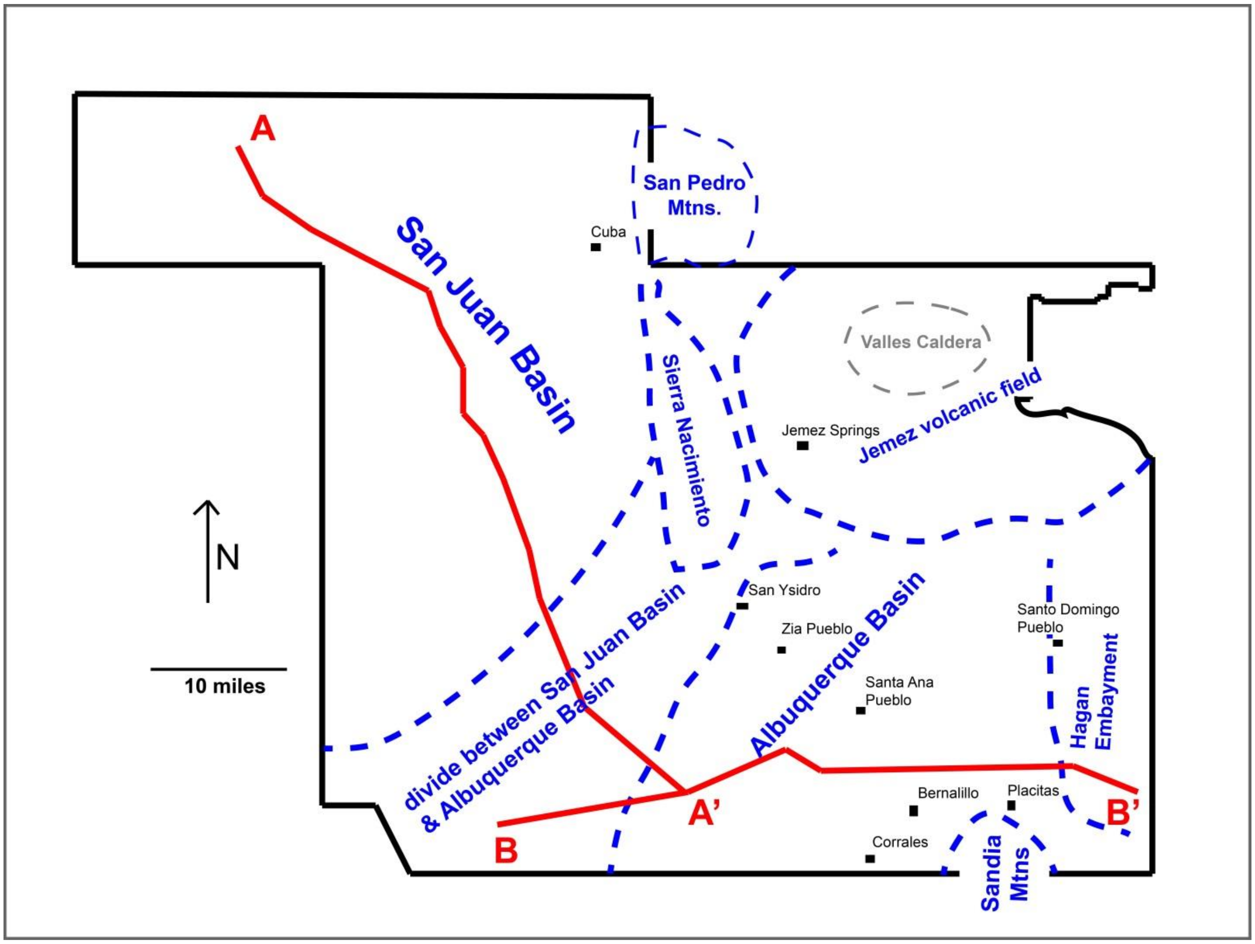


Figure 2. Outline of Sandoval County, showing major geologic elements within the county. Also shown are the locations of cross section A-A' (Figure 4) and cross section B-B' (Figure 5).

The Sandia Mountains are located in the southeastern part of the county. Most of the Sandias are located to the south in Bernalillo County. The geology of the Sandia Mountains is similar to the geology of the Sierra Nacimiento from an oil and gas perspective. The mountains are bounded on the west by steeply dipping faults that separate the mountain range from the Albuquerque Basin. Precambrian rocks are exposed in the higher parts of the mountains and Pennsylvanian and Permian sedimentary rocks are exposed along the eastern flank. For reasons strikingly similar to those applicable in the Sierra Nacimiento, the oil and natural gas potential of the Sandia Mountains is zero to very low.

All of the mountain ranges in Sandoval County are sparsely populated. The aquifer systems are diverse within them, but generally consist of shallow alluvial aquifers with shallow depths-to-water, fractured Pennsylvanian and Permian limestone aquifers that, once again, have shallow depths and shallow water tables, and isolated fractured bedrock aquifers that are small in area, generally have deep water tables and generally have deep well completion depths. If oil and gas development was to occur in this region, it is highly susceptible to surface contamination because of shallow water tables. However, given the sparse population and the low oil and gas potential of the regions, there is a low risk of contamination affecting populations.

The southeastern flank of the San Juan Basin occupies northwestern and west-central Sandoval County (Figure 2). This is the part of the county that has been productive of oil and natural gas since the 1950's. Most of the production has taken place in the panhandle of the county and along the northern boundary of the county. Within the San Juan Basin part of Sandoval County, most productive wells are located within 20 miles of the Rio Arriba county line. Production has been obtained mainly from Upper Cretaceous strata with the Mancos Shale having contributed most of the oil production. The main oil productive zone is the Mancos C, which lies at the base of the Upper Mancos Shale. The Mancos C is 3,500 ft to 5,400 ft deep where it is productive. The Jurassic Entrada Sandstone has contributed minor production from small scattered oil reservoirs. More scattered production has been established further to the southeast to approximately 25 miles south of the Rio Arriba county line and is west of the Rio Puerco. Oil and gas potential decreases southward primarily because petroleum source rocks, including the Mancos Shale, become less mature in this direction. In the far northwestern part of the county, Cretaceous and Jurassic source rocks have been thermally matured into the lower part of the oil window and are at the stage of optimum oil generation. As one moves to the south and southeast, burial depths of source-rock bearing strata become shallower and thermally maturity of the source rocks decreases. As the divide (or transition) between the San Juan and Albuquerque Basins is reached, source rocks in the Cretaceous and Jurassic sections have become progressively less mature and oil and natural gas potential becomes correspondingly low.

Establishment of adequate levels of oil production from the Mancos has always required artificial fracturing. Since 1950, hydraulic fracturing has been used to initiate artificial fractures in vertical wells. Within the last 6 years, wells have been drilled horizontally and subsequently hydraulically fractured through the Mancos Shale reservoirs. This has resulted in significantly increased production when compared to vertically drilled wells. Thus far, horizontal drilling in the Mancos has been confined to the far northwestern part of Sandoval County and good results (profitable oil and gas production) have been obtained. Horizontal drilling has not thus far been applied farther to the southeast near the southeastern limit of established Mancos production. It is not clear if horizontal drilling will be economically viable in this area where the Mancos has only been matured to the uppermost part of the oil window.

Within the Colorado Plateau/San Juan Basin and the transition to the southeast toward the Albuquerque Basin, the primary aquifers are in alluvial fill (shallow well depths and depth-to-water), the San Jose Formation (shallow well depths and depths-to-water) and the Ojo Alamo Formation (shallow well depths and depth-to-water). Secondary aquifers are present in isolated parts of the Nacimiento Formation, fractured volcanic rocks and in fractured Cretaceous sandstones. These have variable well depths and depths-to-water. The region is sparsely populated, with the major towns present along the front of the Sierra Nacimiento. Several thousand feet of sedimentary rock exists between the primary aquifers and the likely target petroleum reservoirs, including thick intervals of shale. The thickness and low permeability of rocks between aquifers and reservoirs means that the region has low susceptibility to upward leakage of brines and organic contaminants from the reservoir into the aquifer. The region has extensive historical oil and gas development, opening the possibility of upward flow along old, leaky boreholes during hydraulic fracturing, creating a moderate susceptibility to contamination along this flow path. Shallow water tables and shallow well depths make the aquifers moderately to highly susceptible to surface contamination from oil and gas operations. However, the sparsity of population makes the overall contamination risk low. Care in petroleum operations should be taken around homes, towns and streams.

The northern part of the Albuquerque Basin extends northward into south-central Sandoval County from Bernalillo and Valencia Counties. This rifted basin is extensively faulted and is formed by down-dropped fault blocks that are shallowest on the western and eastern flanks of the basin and become progressively deeper in the direction of a central north-south trending axis. In addition, the central axis of the basin is substantially deeper to the south in Bernalillo and Valencia Counties. The faults that form the basin developed mostly during the Tertiary. As a result, Cretaceous strata, which are the principal oil and gas productive strata in the San Juan Basin, are deepest along the central axis of the basin and shallowest in the shallower fault blocks along the eastern and western basin margins. Tertiary sediments, including sands, conglomerates and shales, are also thickest along the basin axis. Within the Sandoval County part of the Albuquerque Basin the Tertiary section is more than 4,000 ft thick along the basin axis. To the south in Bernalillo County, Tertiary sediments exceed 17,000 ft in thickness. The Mancos C, which is the main target for drilling in northwestern Sandoval County, is thermally immature where it has been preserved in the shallow fault blocks on the eastern and western flanks of the Sandoval County part of the basin. It has not generated oil in these areas and will be nonproductive. Further towards the center of the basin where it has been buried more deeply, the Mancos C has been matured to the uppermost part of the oil window and is in the early stages of oil generation. The Mancos C production will be less than optimal and thermal maturity levels suggest that it may be comparable to Mancos C production at the southeastern limit of production in the San Juan Basin where the Mancos C has also been matured to the uppermost part of the oil window. In a narrow area along the basin axis, which is roughly coincident with the Rio Grande, the Mancos C is buried more deeply and has been matured to the lower part of the oil window or perhaps even into the thermogenic gas window.

Perhaps an optimal target for oil exploration in the Sandoval County part of the Albuquerque Basin is the Jurassic Entrada Sandstone. The Entrada is present at greater depths than the Mancos. The Todilto limestones, which are the source rocks for oil reservoired in the

Entrada, are thermally more mature than the Mancos and approach optimum thermal maturity. The Entrada is a conventional oil reservoir that is highly porous and permeable. Because of the high porosity and permeability, any oil accumulations that may be present within the Entrada could be developed by vertical, as opposed to horizontal wells. In a highly permeable reservoir such as the Entrada, hydraulic fracturing is not required to initiate adequate levels of production.

Deeper targets in Triassic, Permian and Pennsylvanian strata within the Albuquerque Basin are likely to be barren of oil and gas. Although they are thermally mature, there do not appear to be any appreciable volumes of petroleum source rocks present within these strata. Therefore, no oil or gas has been generated and none will be present.

The major aquifers in the Albuquerque Basin are in alluvium, and in several older basin-fill sand units. The older units include the Arroyo Ojito and Cerro Conejo Formations west of the Rio Grande valley, the Sierra Ladrones Formation along the axis of the valley, and the piedmont Sierra Ladrones Formation along the base of the Sandia Mountains. Several thousand feet of sediment these units from potential target petroleum reservoirs, making upward flow of contaminants in the drinking water aquifer unlikely. However, the faults and fractures of the region do show signs of being permeable in some locations, making them a moderately susceptible flow path. The area has few existing deep oil and gas wells, so the Albuquerque Basin has low susceptibility to flow up leaky boreholes.

The Albuquerque Basin is, in places, highly susceptible to surface contamination. In the modern Rio Grande valley, water tables (10-50 ft bgs, below ground surface) and well depths (<200 ft) are shallow, making the modern Rio Grande valley highly susceptible to surface contamination. The water table becomes deeper away from the valley, either to the east or west, where depth to water increases to several hundred feet. These regions have low susceptibility to surface contamination.

However, in Sandoval County, the Albuquerque Basin contains much of the northern Albuquerque Metropolitan Area, several Pueblos, and a dense string of small agricultural communities lining the Rio Grande. Most of these communities are reliant on groundwater as their sole source of drinking water. Consequently the risk of contamination associated with oil and gas operations is high—accidental spills and leaks can have serious consequences for nearby water users.

To the northeast, the Albuquerque Basin underlies the Jemez Mountains volcanic field. Northeastern Sandoval County has been very sparsely drilled. Therefore, the subsurface geology of this part of the county is poorly understood. The very limited data indicate that Triassic, Permian and Pennsylvania strata, are present below the volcanic cover but that strata of Jurassic and Cretaceous age appear to be absent to the west but may be present to the east. However, the intense heat associated with Tertiary and Quaternary volcanic activity and accompanying pervasive volcanic intrusion in the subsurface may have acted to naturally crack any previously existing oil into natural gas. Furthermore, the rising volcanic magmas carried substantial volumes of carbon dioxide, which exsolved from the rising magmas. This carbon dioxide enters reservoirs that the magmas come in contact with and dilutes any hydrocarbon gases that may be present. This produces gases with low heating values that are commercially undesirable. Therefore, the oil and gas potential of northeastern Sandoval County is low.

Around the Jemez Mountains volcanic field in Sandoval County, aquifers are generally in alluvium along the valleys or locally in fractured volcanic rocks. The alluvial aquifers have shallow water tables and shallow well depths, making them highly susceptible to surface contamination. The fractured aquifers are highly variable in well depth and depth to water. The low oil and gas potential and the relatively low population density of the region result in a low risk of contamination. Once again, homes, communities and streams should be avoided during oil and gas development.

STRATIGRAPHY of OIL and GAS ZONES

Rocks and sediments in Sandoval County range in age from Precambrian to Recent. Pennsylvanian, Permian, Triassic, Jurassic and Cretaceous strata are present throughout most of the county and are underlain by Precambrian crystalline basement rocks (Figures 3a, 3b). The Precambrian rocks are exposed in the Sierra Nacimiento, San Pedro and Sandia Mountains. Tertiary-age sedimentary rocks and sediments occur in thick sections in the Albuquerque Basin. Tertiary-age basalt flows are present at the surface in the southwestern part of the county as are small intrusive bodies of volcanic rocks that have been exposed at the land surface by erosion. The most obvious of these exposed intrusive bodies is Cabezon Peak. The northeastern part of the county is characterized by large complexes of Tertiary and Quaternary volcanic and plutonic igneous rocks that form the Jemez Mountains volcanic field. The subsurface geology of large portions of the northeastern part of the county is largely unknown because of a paucity of drill holes that have penetrated rocks in the subsurface, but is most likely characterized by Paleozoic and Mesozoic strata that have been intruded by Tertiary and Quaternary igneous rocks.

The stratigraphy of the Precambrian and layered Paleozoic, Mesozoic and Tertiary strata is summarized in Figure 3 and is portrayed in cross sections A-A' and B-B' (Figures 4, 5; oversized versions in Appendix A). Tertiary-age strata in the Albuquerque Basin have different nomenclature than Tertiary-age strata in the San Juan Basin. The nomenclature of each basin is portrayed in the cross sections. For more detailed descriptions of the sedimentary rocks in the county, please refer to Molenaar (1977), O'Sullivan (1977), Ridgely (1977), Green and Pierson (1977), Vincelette and Chittum (1981), Baars and Stevenson (1977), Jentgen (1977), Armstrong and Mamet (1977), Kelley (1977), Woodward (1987), Connell and others (1998) and Connell and others (1999).

AGE	STRATIGRAPHIC UNITS		DESCRIPTION	THICKNESS (ft) (where not eroded at outcrop)
Tertiary	varied between San Juan Basin and Albuquerque Basin (see text)		nonmarine fluvial to alluvial sands, gravels and light- to dark-gray lacustrine (lake) shales	2500 ft maximum in northwest Sandoval County; 1900 -5200 ft in Sandoval Co. part of Albuqerque Basin.
Late Cretaceous	Kirtland Shale		gray nonmarine shales and minor sandstone	150 - 400
	Fruitland Formation		carbonaceous shales and coals interbedded with sandstones and siltstones	
	Pictured Cliffs Ss			90 - 130
	Lewis Shale		dark-gray marine shales	300 - 1600
		Chacra sands	marine-shelf sandstones interbedded with dark-gray marine shales	
			dark-gray marine shales	
	Cliff House Ss		coastal sandstones	10 - 100
	Menefee Fm		nonmarine fluvial sandstones, shale, coals	100 - 1000
	Point Lookout Ss		coastal barrier sandstones	90 - 275
	Upper Mancos Shale	Mancos A	dark-gray marine shales with minor thin beds of fine-grained marine shelf sandstones	500 - 1000
		Mancos B		
		Mancos C	dark-gray marine shales with more fine-grained marine shlef sandstones than in Mancos A and Mancos B	200 - 600
	Lower Mancos Shale	upper Carlile shale	dark-gray marine shales	120 - 500
		Juana Lopez	dark-gray marine shales with thin beds of marine shelf sandstones & thin bedded detrital limestones	60 - 180
		lower Carlile shale	dark-gray amrine shale. Discontinuous Semilla Ss in upper part	100 - 350
		Greenhorn Limestone	dark-gray calcareous shale with thin limestone beds	15 - 30
		Graneros Shale	dark-gray marine shale. Laterally intertongues with upper part of Dakota Sandstone	230 - 525
	Dakota Sandstone		marine sandstones interbedded with marine shales	
Precambrian through Jurassic rocks (see Fig. 3b, next page)				

Figure 3a. Stratigraphic chart of Cretaceous and Tertiary rocks in Sandoval County, exclusive of Tertiary volcanic and intrusive igneous rocks.

AGE	STRATIGRAPHIC UNITS	DESCRIPTION	THICKNESS (ft) (where not eroded at outcrop)
Cretaceous through Tertiary rocks (see Fig. 3a, previous page)			
Jurassic	Morrison Fm	nonmarine fluvial to lacustrine sandstones & shales	300 - 1000
Jurassic	Summerville Fm	sands, siltstones and fine-grained silty sandstones deposited on inland sabkhas, present as erosional remnants in subsurface	0 - 30
Jurassic	Todilto Fm	organic-rich lacustrine limestones overlain by anhydrite	5 - 125
Jurassic	Entrada Sandstone	fine- to medium-grained well-sorted eolian sandstone	20 - 330
Triassic	Chinle Fm	red nonmarine fluvial to lacustrine shale with sandstone lenses. Agua Zarca Sandstome Member present locally at base.	870 - 1200
Permian	Bernal Formation	maroon shales, present as erosional remnants in subsurface	50 - 140
Permian	Glorieta Ss (north) San Andres Ls (south)	fine- to medium-grained marine to marginal marine sandstones (Glorieta); upper part of Glorieta transitions to San Andres marine limestone towards the south	40 - 130
Permian	Yeso Formation	red to orange marine shales, fine-grained sandstones & anhydrites	230 - 550
Permian	Abo Formation	nonmarine alluvial red shales and fine- to coarse-grained sandstones	870 - 1660
Pennsylvanian	undivided	marine limestones, red shales & sandstones with minor gray shales	580 - 1500
Mississippian		marine limestone, present as erosional remnants in subsurface	0 - 150
Precambrian		granitic igneous rocks, monzonites, mafic igneous rocks, metamorphosed sedimentary & volcanic rocks	

Figure 3b. Stratigraphic chart of Precambrian through Jurassic rocks in Sandoval County.

Figure 4. Northwest-southeast structural cross section through Sandoval County. See Figure 2 for location.

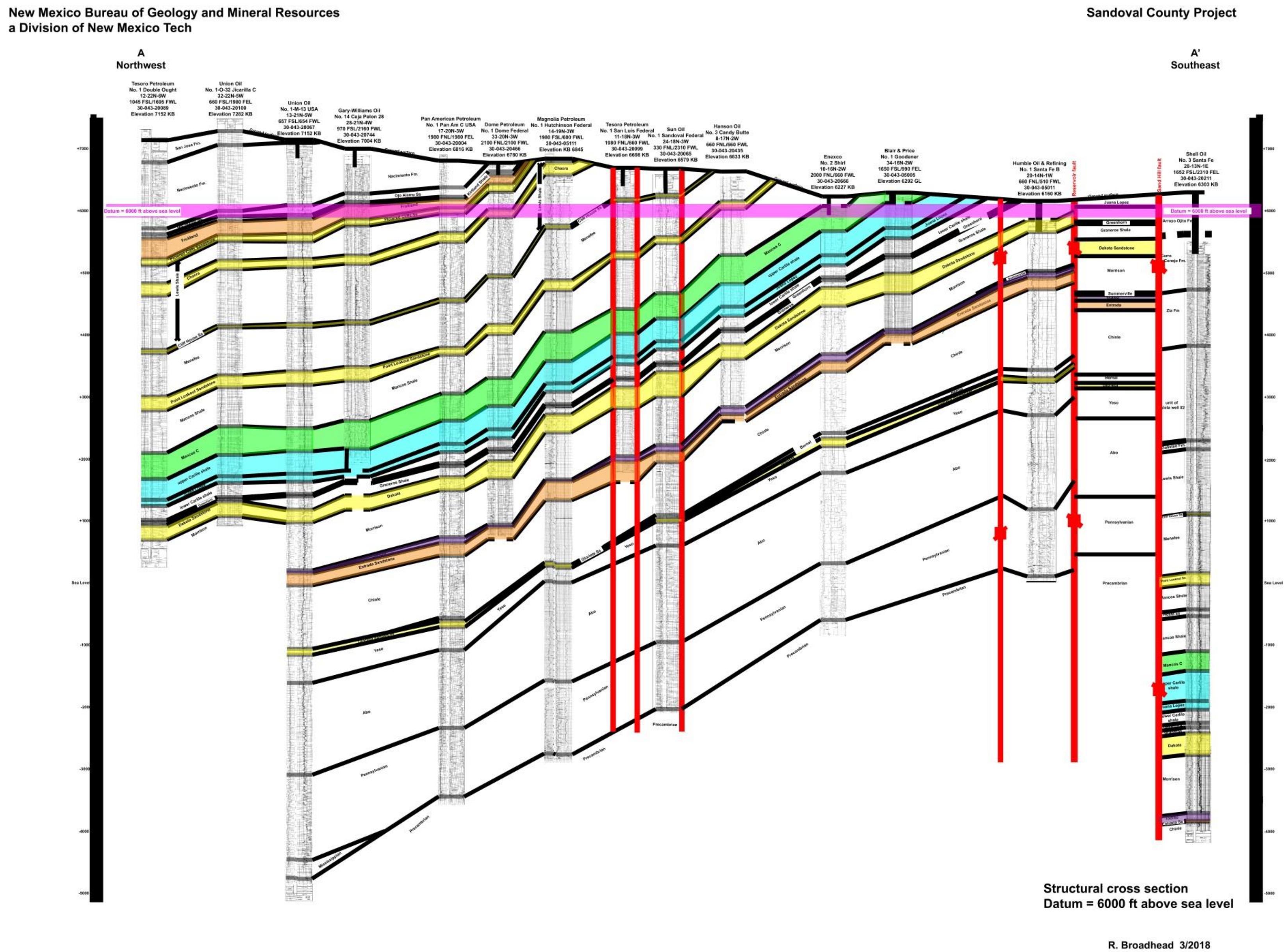
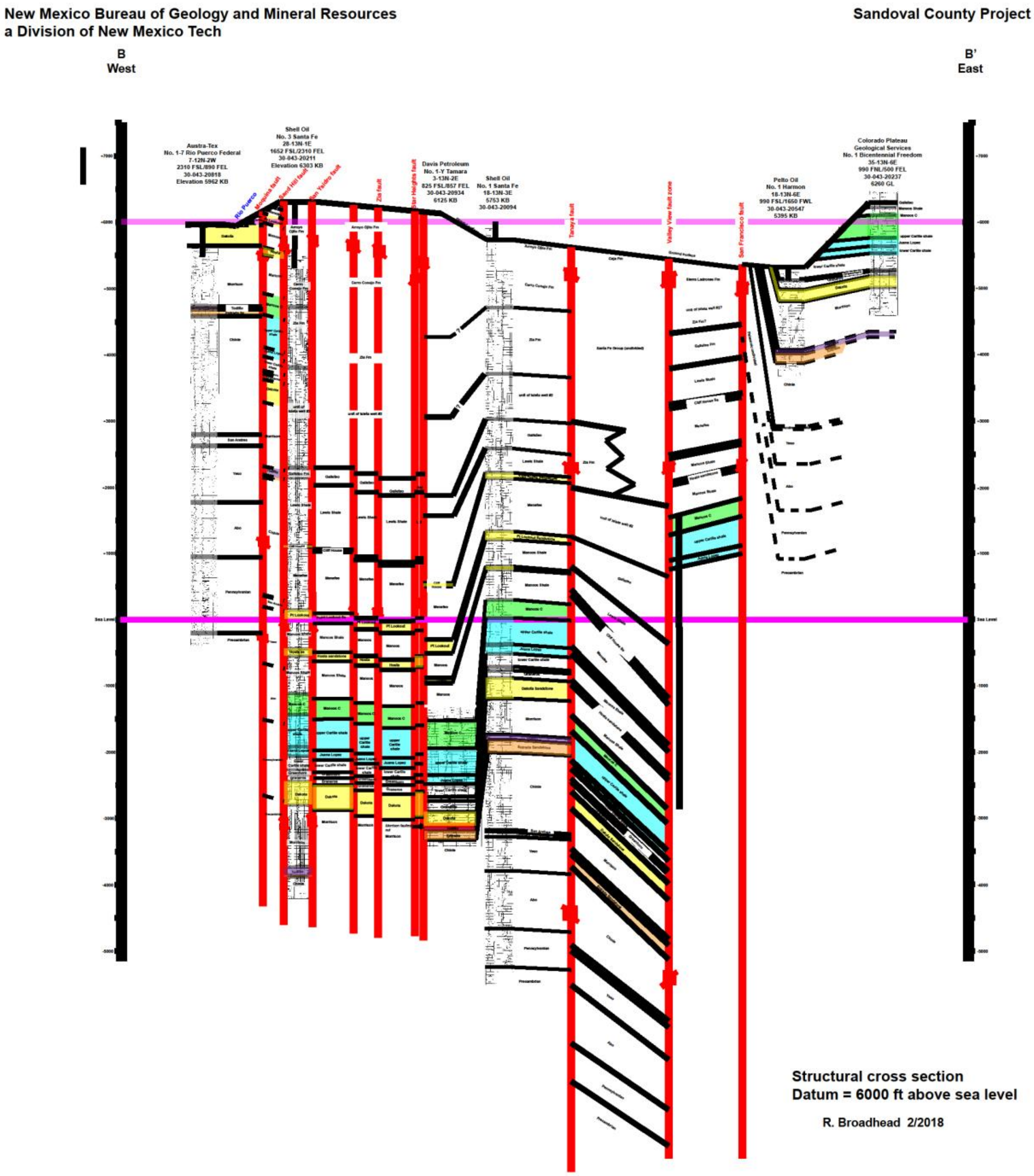


Figure 5. West-east structural cross section through Sandoval County. See Figure 2 for location.



GEOLOGICAL STRUCTURE

The major structural elements of Sandoval County (Figure 2) are the mountain ranges (Sierra Nacimiento, San Pedro Mountains, Sandia Mountains), the San Juan Basin in the northwest, the Albuquerque Basin in the south-central part of the county, the divide (or transition) between the Albuquerque and San Juan basins in the southwest part of the county, and the Valles Caldera and surrounding Jemez Mountains volcanic field in the northeast. The Hagan Embayment of the Espanola Basin pokes its nose into the southeastern most part of the county just to the northeast of the Sandia Mountains.

The southeastern end of the San Juan Basin is present in northwestern Sandoval County. Strata rise to the southeast out of the San Juan Basin and are truncated at the land surface as they reach the divide between the San Juan and Albuquerque Basins (Figure 4, oversize version in Appendix A). To the east, the boundary between the San Juan Basin and the Sierra Nacimiento/San Pedro Mountains is formed by the reverse faults that brought the Precambrian cores of the mountain ranges upward where they overlook Cretaceous and older strata that infill the San Juan Basin (Figure 6, oversize version in Appendix A; Woodward, 1987). The Puerco fault belt (Kelley, 1977) extends northeast-southwest across the divide between the San Juan and Albuquerque Basins. The Puerco fault belt consists of a series of normal faults, most of which are downthrown toward the west (Hunt, 1936).

The Sierra Nacimiento and the San Pedro Mountains are formed by large upthrown fault blocks bounded on their western sides by the reverse faults that separate these mountains from the San Juan Basin. The mountain blocks dip eastward. Outcrops vary from Precambrian basement rocks along the mountain crests to Pennsylvanian and Permian strata on the eastern flanks of the mountains. The Pennsylvanian and Permian strata dip eastward and dive under the Tertiary- to Quaternary-aged volcanic rocks of the Jemez Mountains volcanic field to the east. The Valles caldera forms the center of the Jemez Mountains volcanic field. Within the Valles caldera, more than 6,000 ft of volcanic rocks are present and extend from the land surface downward into thesubsurface. The subsurface structure and stratigraphy of Sandoval County east of the Sierra Nacimiento are poorly understood because of a scarcity of exploratory wells over most of this area outside of blocks that have seen geothermal exploratory drilling.

The Sandia Mountains extend northward from Bernalillo County into southeastern Sandoval County. The Sandia Mountains are separated from the Albuquerque Basin on the west by normal faults that have down-dropped the Precambrian rocks exposed along the mountain face deep into the basin. From the crest of the Sandias, rocks dip eastward into the subsurface. The eastern flank of the mountains is covered by Pennsylvanian and Permian strata. At the northeastern end of the Sandia Mountains northeast of Placitas, Pennsylvanian and Permian strata dip into the Hagan embayment where they are overlain by Triassic, Jurassic, Cretaceous and Tertiary strata.

Figure 6. Structure contours on Mancos C. Contours are in feet with respect to sea level.
For well data utilized in making this map, see database ***Sandovalwells.xls*** in Appendix B.

Mancos C Structure

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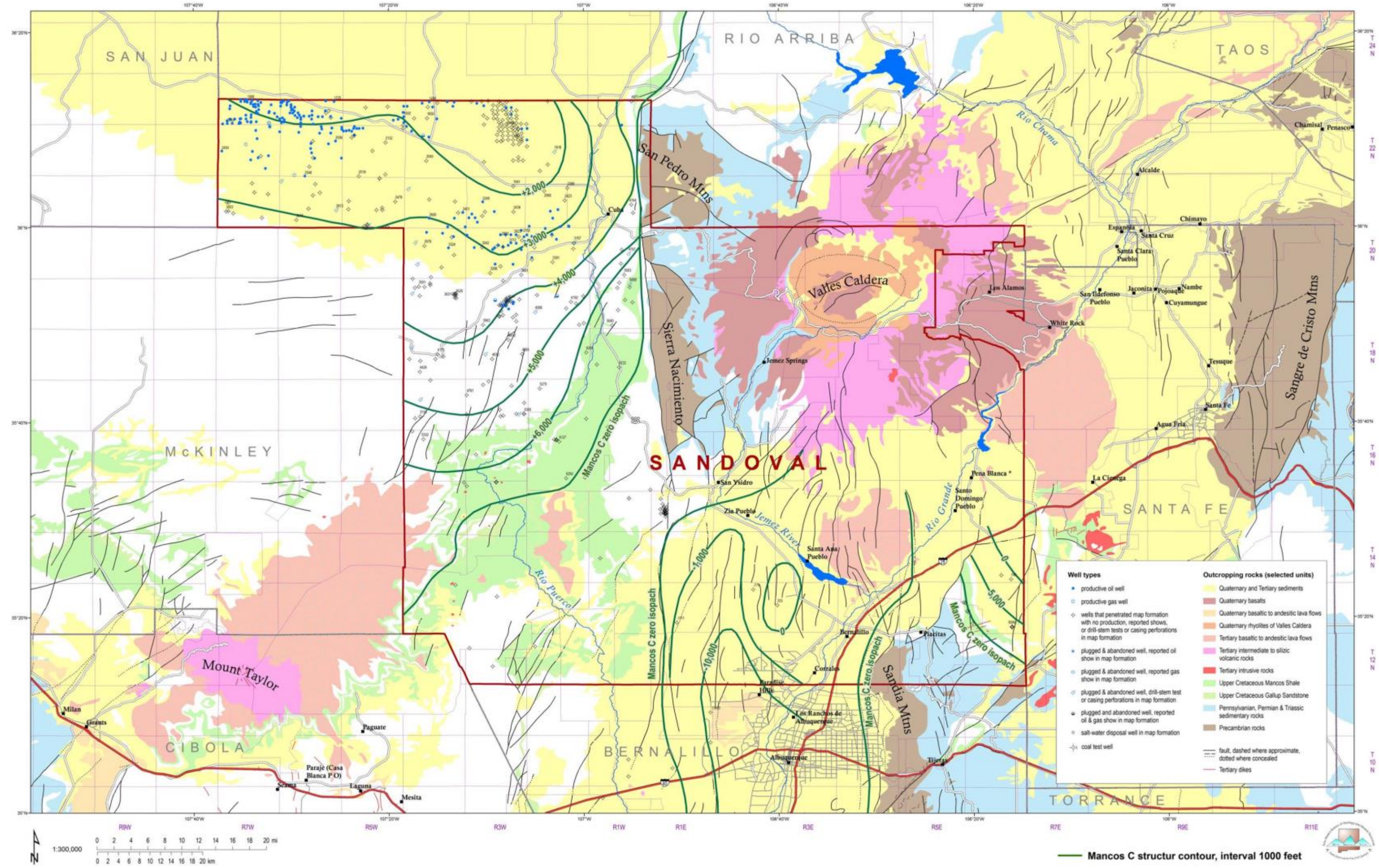

The Albuquerque Basin lies west of the Sandia Mountains. The northern part of the basin extends into south-central Sandoval County (Figure 2; Figure 6, oversize version in Appendix A). Although it appears relatively simple on the surface, the Albuquerque Basin is structurally complex in the subsurface. Connell (2008b) presented several east-west geologic cross sections that depict the basin in the subsurface. Rocks exposed in outcrops east and west of the basin have been down-dropped into the basin by a series of faults on the east and west sides of the basin, forming a stair step geometry. The faults are listric; that is they flatten with depth. On cross section B-B' of this report that cuts east-west across the Albuquerque Basin (Figure 5, oversize version in Appendix A), the major faults seen on Connell (2008b)'s cross sections appear as vertical lines, a consequence of the vertical exaggeration needed to display the details of the stratigraphy. Black and Hiss (1984) presented a more generalized east-west cross section through the northern part of the Albuquerque Basin that cuts through the Shell No. 1 Santa Fe Pacific well, which is shown in cross section B-B' of this report (Figure 5, oversize version in Appendix A). The Mancos C unit, which is the primary oil-productive stratum in the Sandoval County part of the San Juan Basin, is present at depths of more than 7,000 ft in the Sandoval County part of the Albuquerque Basin (Figure 7, oversize version in Appendix A). To the south in Bernalillo County, the basin becomes much deeper and depth to the Mancos C is more than 17,500 ft. The basin formed during Late Tertiary rifting and as the fault blocks within the basin subsided the basin was infilled with Tertiary sediments derived from bordering highlands. As a result the Tertiary strata, which contain the basin's aquifers, are thicker in the deeper parts of the basin. The Tertiary section has a maximum thickness of more than 4,000 ft in Sandoval County (Figure 8, oversize version in Appendix A). To the south in Bernalillo County, the Tertiary attains a maximum thickness of 17,780 ft in the Shell No. 1 West Mesa Federal well, an unsuccessful exploratory test drilled in Section 24, T11N, R1E in 1981 that encountered substantial gas shows. See Black (1982) for a discussion of this well.

OIL and GAS PRODUCTION

Oil and natural gas have been produced from Sandoval County since the 1950's. Table 1 lists cumulative production in the county through the end of 2017 as well as annual production of oil, natural gas, and oilfield waters during 2017. There are currently 533 active oil and gas wells in the county. A total of 1138 wells have been drilled in the county; 261 have been productive of gas and 390 have been productive of oil. A list of the wells drilled in the county that includes selected data for each well is given in the database ***Sandovalwells.xls*** which is presented in Appendix B.

Production has been established from the northwestern part of the county, from areas north of the town of San Luis and, except for one well, west of the Rio Puerco. Gas has been produced from the Fruitland Formation (Cretaceous), the Pictured Cliffs Sandstone (Late Cretaceous), and the Chacra sandstone interval within the Lewis Shale (Late Cretaceous). Oil

Figure 7. Contours of depth to top of Mancos C. For well data utilized in making this map, see database ***Sandovalwells.xls in Appendix B.***

Depth to Mancos C

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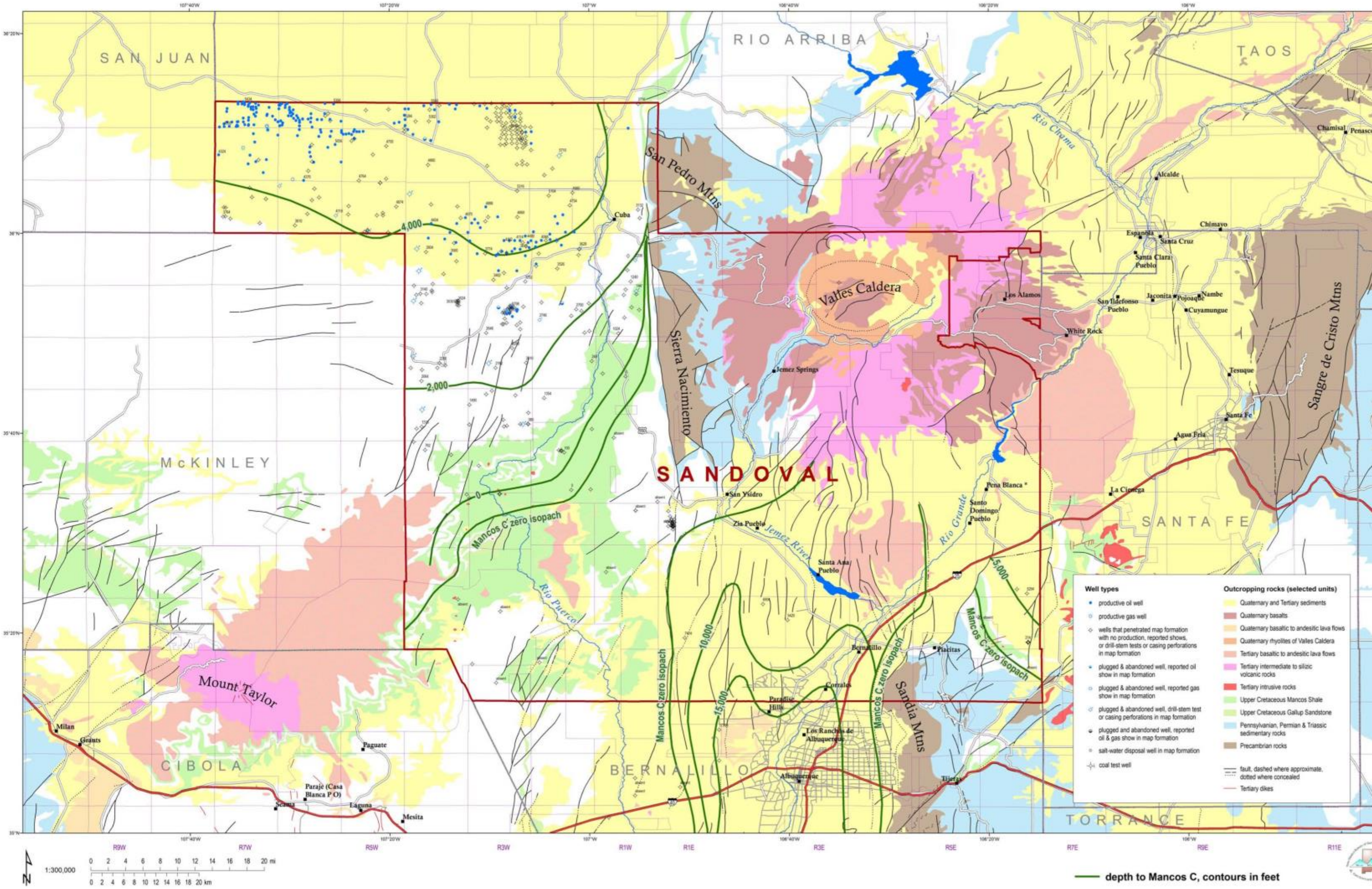
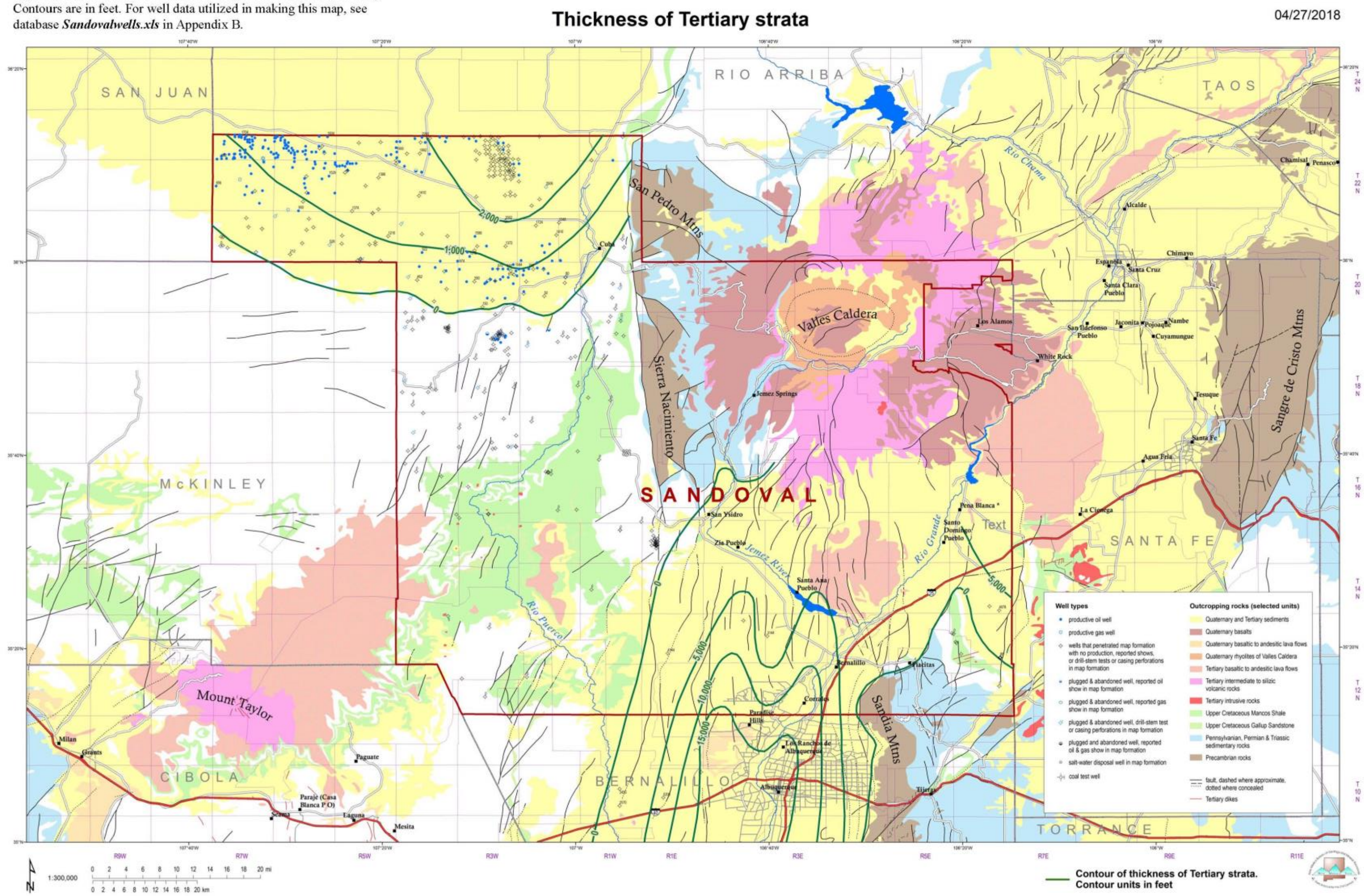


Figure 8. Contours of thickness of Tertiary strata in Sandoval County. Contours are in feet. For well data utilized in making this map, see database ***Sandovalwells.xls*** in Appendix B.



and associated gas have been produced from the Menefee Formation (Late Cretaceous), the Upper Mancos Shale (Late Cretaceous), the Lower Mancos Shale (Late Cretaceous), the Dakota Sandstone (Early-Late Cretaceous), and the Entrada Sandstone (Jurassic). The following sections describe the nature of the oil and production in each of the aforementioned stratigraphic units ("formations").

Table 1. Cumulative and annual 2017 production of oil, natural gas, and oilfield water from Sandoval County. **BO**, barrels oil; **MCFG**, thousand ft^3 natural gas, **BW**, barrels water. Data are through the end of 2017. Data from 1994 through 2017 obtained from the website of the New Mexico Oil Conservation Division. Data prior to 1994 obtained from published 1993 Annual Report of the New Mexico Oil & Gas Engineering Committee.

	Cumulative production as of December 2017	**Annual production during 2017**
oil	17,938,646 BO	1,362,028 BO
natural gas	142,842,314 MCFG	12,092,302 MCFG
water	99,248,378 BW	1,683,927 BW

Nacimiento Formation (Tertiary)

The Nacimiento Formation, with its interbedded lacustrine shales and fluvial to alluvial sandstones, is not productive within Sandoval County. However it is mentioned because it is productive from minor gas pools in the San Juan Basin. The nearest Nacimiento gas pool is Gavilan Nacimiento (Dugan, 1983) which is located approximately 10 miles north of the Sandoval – Rio Arriba County line in Sec. 6, T24N, R1W and in Sec. 12, T24N, R2W. The pool was productive from lenticular Nacimiento sandstones at depths of 3100 ft to 3450 ft. The pool was discovered and brought into production during 1980. Production was obtained from three wells, all of which have been plugged and abandoned. The source rocks for the gas may be dark-gray lacustrine shales in the Nacimiento. At the Arch gas pool in northeastern San Juan County, Emmendorfer (1983) postulated that the gas source rock may be thin coal beds in the Nacimiento Formation and that the gas migrated into adjacent sandstones after generation. Alternatively, the gas may be thermogenic and may have leaked upward from deeper sources such as the Fruitland Formation. At any rate, gas discoveries within Tertiary strata in the San Juan Basin are spurious and have been made while drilling wells for deeper objectives. It is quite probable that many small noncommercial to marginally commercial gas accumulations in the Nacimiento have been drilled through, not tested, and not even recognized in efforts to drill deeper, more prolific pay zones (Broadhead, 1986).

Fruitland Formation (Upper Cretaceous)

The Fruitland Formation, with its interbedded coals, shales and sandstones, has produced natural gas prolifically within the San Juan Basin. Fruitland production has been obtained primarily from the coal beds with a relatively minor amount of gas produced from the sandstones (see Whitehead, 1993a). The most prolific Fruitland coal gas (or coalbed methane) production has been obtained from the deep, northern part of the basin in northeastern San Juan and northwestern Rio Arriba Counties where the Fruitland has been buried more deeply. The deeper burial results in greater thermal maturity of the coals and therefore greater yield per unit volume of coal. Coalbeds are also thicker in the northern area than they are in Sandoval County. Also deeper burial results in greater fluid pressures within the cleat (natural fracture) systems of the coals which results in increased gas storage capacity of the more deeply buried coals.

Gas has been produced from Fruitland coals in northwestern Sandoval County (Fig. 9, oversize version in Appendix A). Depth to productive Fruitland coals in the county varies from 400 to 800 ft. In most of the Sandoval wells, the productive interval is 10 to 20 ft thick. Production of Fruitland gas in the county began in 2005. A cumulative 8.403,931 thousand ft^3 gas has been produced. This represents 5.9% of total cumulative gas production in Sandoval County. A total of 765,350 thousand ft^3 gas were produced during 2017, which is 6.3% of the total gas produced from the county during that year.

Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone (Upper Cretaceous) is productive of gas in northwestern Sandoval County (Fig. 10, oversize version in Appendix A). Two Pictured Cliffs gas pools, Ballard and Blanco South (Brown, 1978a; Brown, 1978b; Whitehead, 1993a), extend southeastward into the county from Rio Arriba County. The Sandoval County parts of the gas pools mark the southeastern extent of Pictured Cliffs production in the San Juan Basin. The northwest-southeast outline of the gas pools follows the northwest-southeast trend of the sandstone bodies that form the Pictured Cliffs reservoirs. In Sandoval County, depth to productive Pictured Cliffs sandstones ranges from 2300 ft to 3200 ft in the Ballard pool and 2800 ft to 3100 ft in the Blanco South pool. Thickness of the productive interval ranges from 30 ft to 100 ft in the Ballard pool and 10 ft to 30 ft in the Blanco South pool. The Pictured Cliffs reservoirs have been developed with vertical wells. The reservoir is hydraulically fractured in order to initiate economic levels of production.

Lewis Shale – Chacra sandstones

The Lewis Shale (Upper Cretaceous) is productive of natural gas in the northwestern part of Sandoval County (Fig. 11, oversize version in Appendix A). Production in the Lewis is obtained from the Chacra sandstones which occur interbedded with shales approximately 300 ft below the top of the Lewis. The Chacra interval is approximately 200 ft thick. The northwest-southeast trend of the productive Chacra wells follows the northwest-southeast trend of the

Figure 9. Wells that have penetrated the Fruitland Formation or, where the Fruitland is not present, older strata in Sandoval County, indicating wells productive of gas from the Fruitland. Outcrop of Fruitland shown in green.

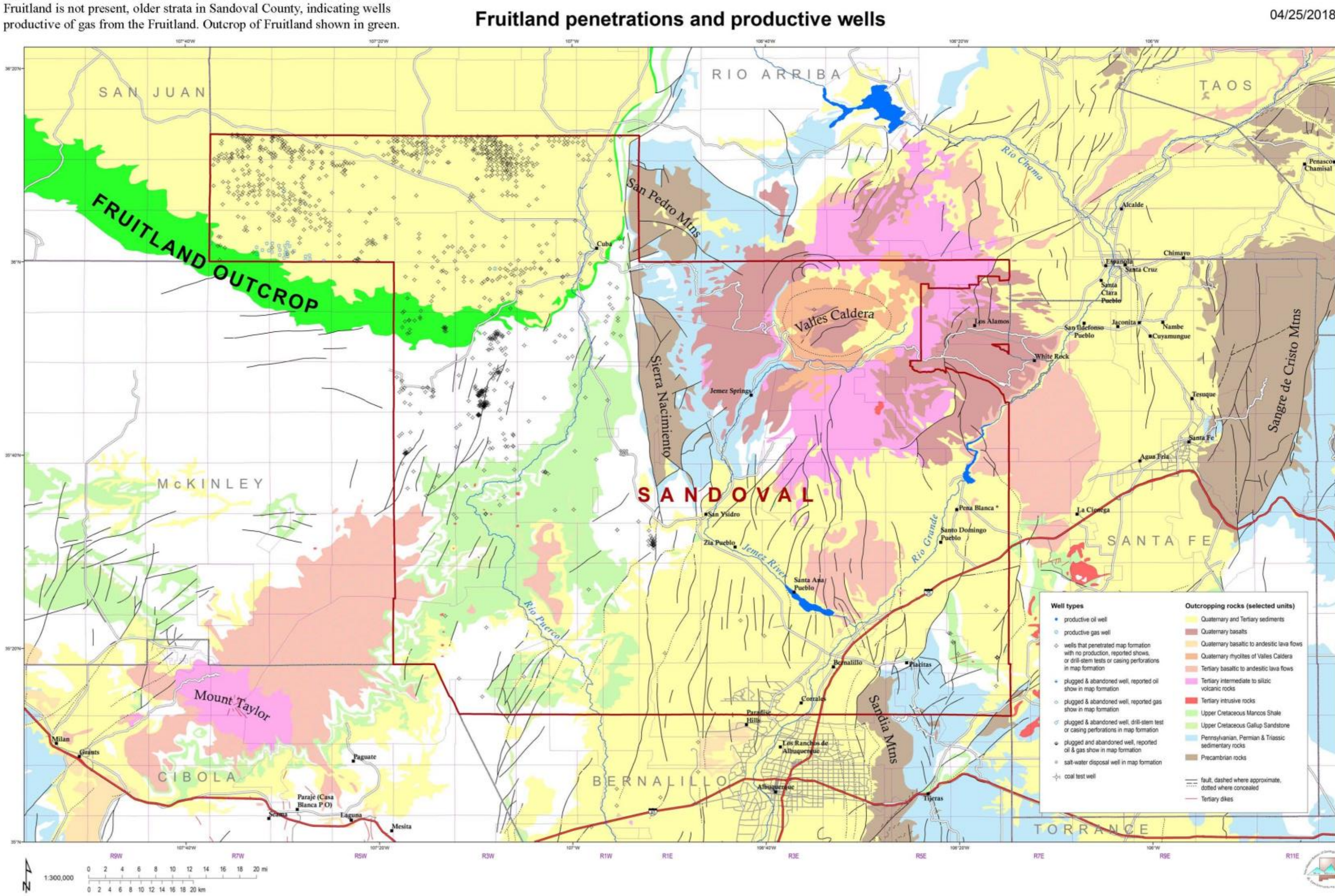


Figure 10. Wells that have penetrated the Pictured Cliffs Sandstone or, where the Pictured Cliffs is not present, older strat in Sandoval County, indicating wells productive of gas from the Pictured Cliffs and unproductive wells that have drill-stem tests or casing perforations in the Pictured Cliffs. Outcrop of Pictured Cliffs shown in green.

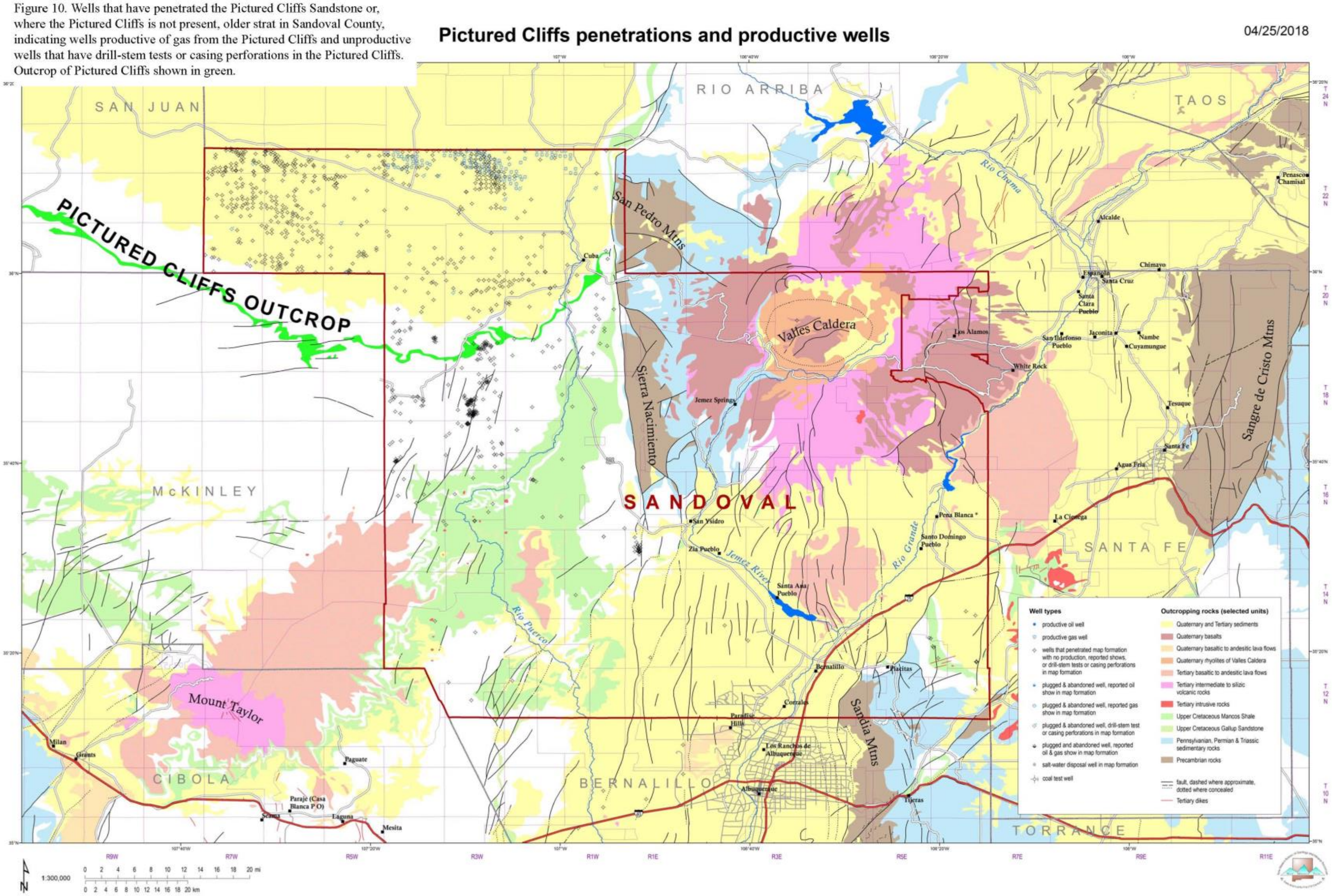
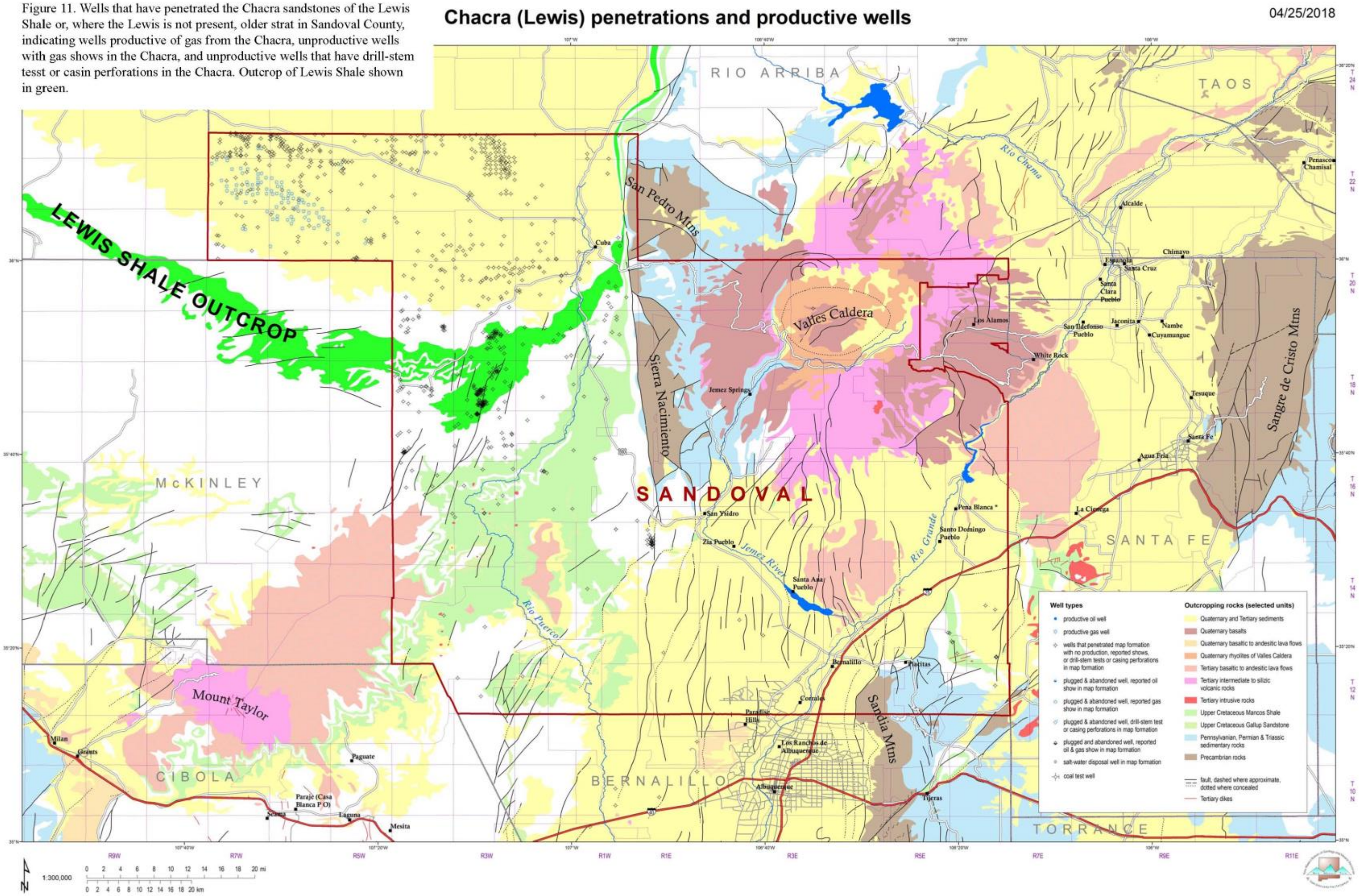


Figure 11. Wells that have penetrated the Chacra sandstones of the Lewis Shale or, where the Lewis is not present, older strat in Sandoval County, indicating wells productive of gas from the Chacra, unproductive wells with gas shows in the Chacra, and unproductive wells that have drill-stem tesst or casin perforations in the Chacra. Outcrop of Lewis Shale shown in green.



Chacra sandstone bodies within the Lewis. In Sandoval County, Chacra production is from the Rusty Chacra gas pool, which was discovered in 1975 (Kennedy, 1978). Depth to Chacra production in the county ranges from 1200 ft to 1800 ft. In most wells approximately 100 ft of the Chacra section has been perforated. The Rusty Chacra pool has been developed with vertical wells. Small hydraulic fracture treatments are necessary to initiate economic levels of production. The fracture treatments increase production by about an order of magnitude or 10 times (see Kennedy, 1978).

Menefee Formation

The Menefee Formation (Upper Cretaceous) has been productive of oil from several small oil pools scattered throughout northwestern Sandoval County (Fig. 12, oversize version in Appendix A). Menefee production is obtained from small, isolated fluvial sandstone lenses encased in shale. Trapping is entirely stratigraphic in most accumulations (Kennedy, 1978; Prichard, 1978). At the San Luis and San Luis South pools the traps are combination structural-stratigraphic and are formed by drape of a fluvial sandstone channel over a structural nose (Higgins, 1983a, 1983b). Depth to Menefee production in Sandoval County ranges from 4,200 ft toward the northwest to 330 ft in the San Luis South pool at the southern limit of established production. Reservoir sandstones range from 5 ft to 20 ft thick and average about 10 ft thick. Menefee oils are light with API gravities in the 40^{o} to 45^{o} range. The Menefee has been developed with vertical wells. Most wells have been completed by perforating cased holes. Most completions do not involve artificial fracturing but some wells have been hydraulically fractured with a sand-water mixture.

Upper Mancos Shale

The Upper Mancos Shale has been productive of oil and associated gas from the northwestern part of Sandoval County (Figure 13, oversize version in Appendix A). The Upper Mancos is the most oil-productive stratigraphic unit in the county. Almost all of the Upper Mancos production has been obtained from vertical wells but almost 70 horizontal wells have been completed in the Mancos. Most of the horizontal wells have been drilled since 2012 but a few pioneering horizontal wells were drilled in the early 1990's.

The Mancos C is the chief productive zone in the vertical wells, although many vertical wells have been variously completed through intervals that also include the lower part of the Mancos B, as well as selected intervals within the Lower Mancos Shale. The Mancos C is 400 to 600 ft thick in the San Juan Basin part of Sandoval County (Figure 14, oversize version in Appendix A). Toward the south and east, it is truncated at the outcrop as it rises out of the San Juan Basin (Cross section A-A', Figure 5, oversize version in Appendix A). The horizontal wells

Figure 12. Wells that have penetrated the Menefee Formation or, where the Menefee is not present, older strata in Sandoval County, indicating wells productive of oil from the Menefee, unproductive wells with oil shows in the Menefee, and unproductive wells that have drill-stem tests of casing perforations in the Menefee. Outcrop of Menefee shown in green.

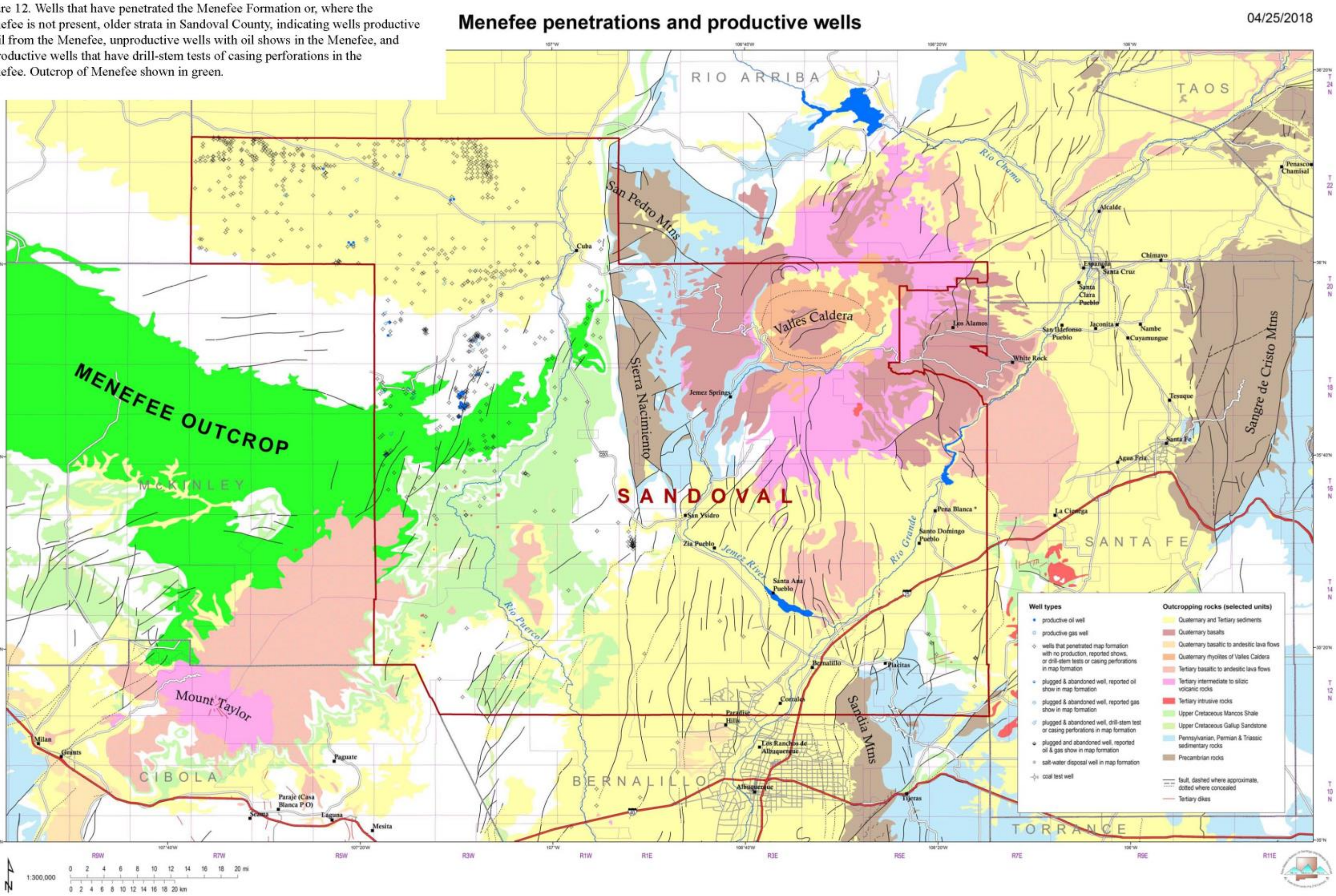


Figure 13. Wells that have penetrated the Upper Mancos Shale or, where the Upper Mancos is not present, older strata in Sandoval County, indicating wells productive of oil from the Upper Mancos, unproductive wells with oil shows in the Upper Mancos, and unproductive wells that have drill-stem tests or casing perforations in the Upper Mancos. Outcrop of Mancos Shale shown in green.

Upper Mancos penetrations & productive wells

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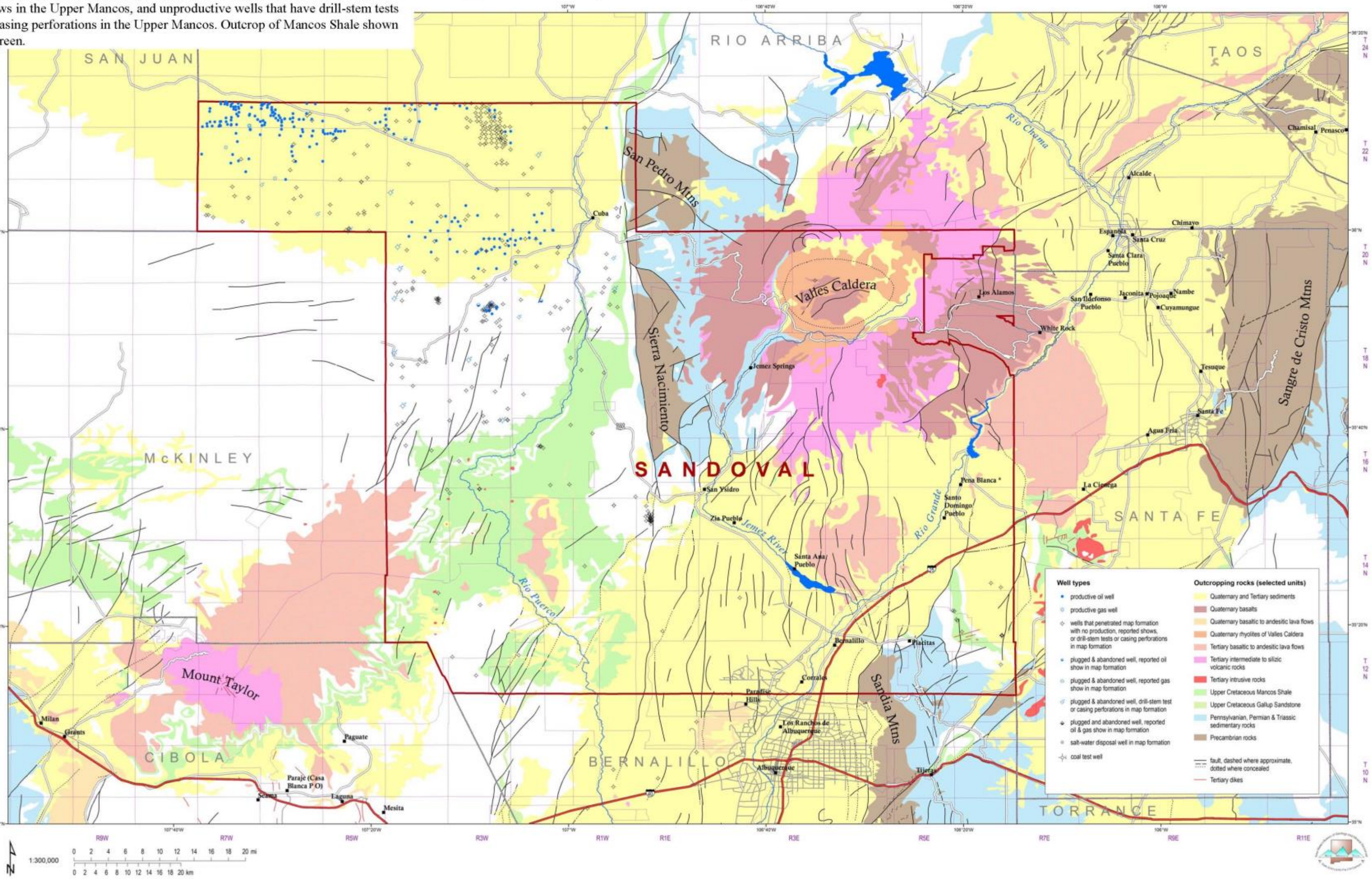
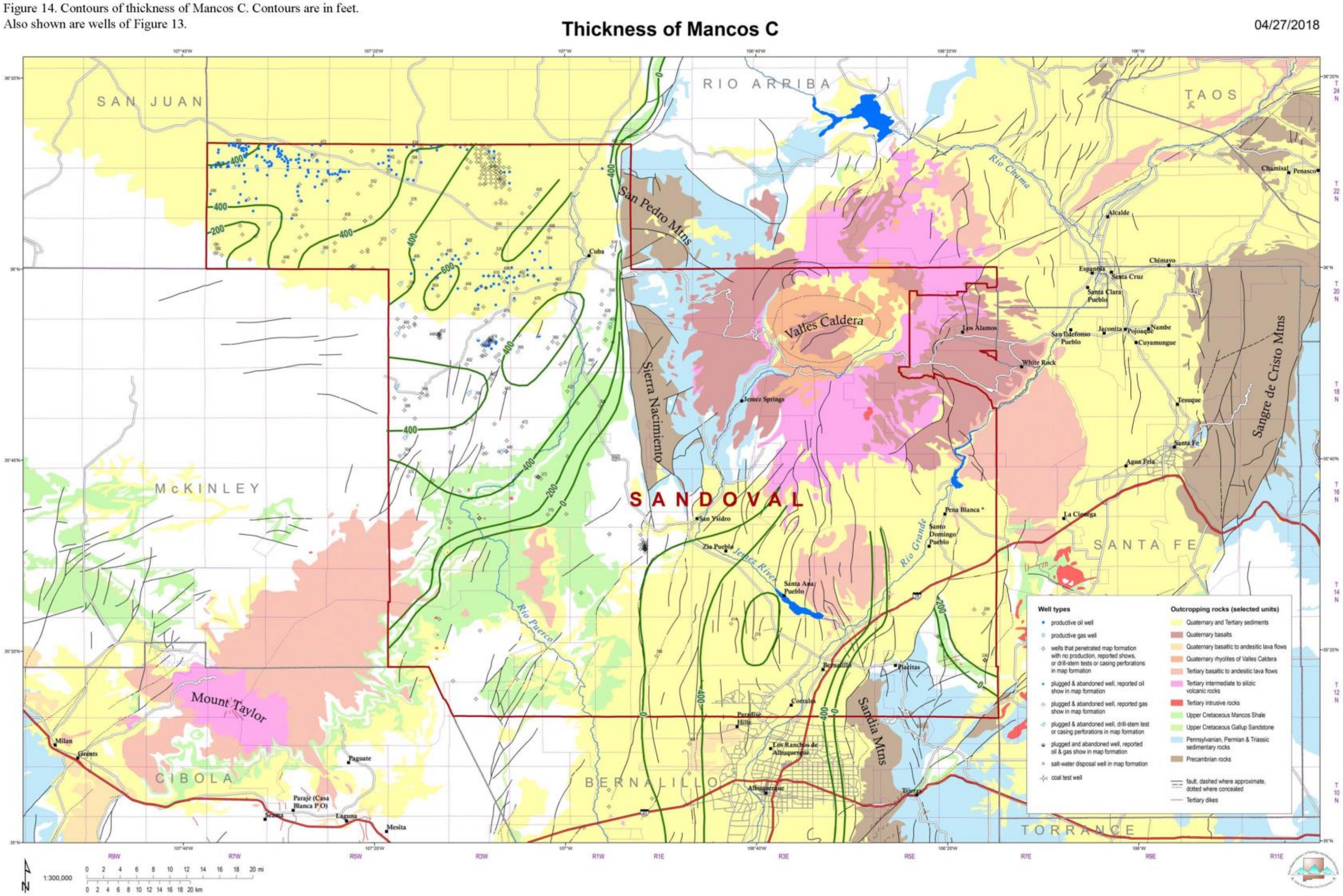


Figure 14. Contours of thickness of Mancos C. Contours are in feet. Also shown are wells of Figure 13.



in the Mancos have all targeted the Mancos C. Oil production from horizontal Mancos wells in the San Juan Basin exceeds oil production from vertical Mancos wells by a multiple of 9.4 during the first 12 months of production. Salient data from eleven horizontal Mancos C wells in Sandoval County are presented in Table 2. All of the horizontal Mancos C wells in Sandoval County are located in the far northwestern part of the county which marks the southeastern extent of the Mancos Shale play in the San Juan Basin (Broadhead, 2015). All of the productive Mancos wells in the west-central part of the county in T19-21N, R2-4W, are vertical. The recent and current Mancos Shale play in the San Juan Basin has utilized mostly horizontal wells.

Depth to the Mancos C ranges from 3,500 ft to 5,400 ft where it is productive in Sandoval County (Fig. 7, oversize version in Appendix A). The Mancos C is deepest in the far northwestern part of the county and rises to the southeast.

Table 2. Production data from eleven horizontally drilled Mancos oil wells drilled in the Sandoval County part of the San Juan Basin. **MBO**, thousand barrels oil; **MMCFG**, million ft^3 natural gas; **MBW**, thousand barrels water.

Operator, well number, well name	API number	Surface Hole Location (section- township-range, county)	Measured depth (feet)	True vertical depth (feet)	Reservoir unit	Completion date (mo/yr)	First 12 months production	Cumulative production December 2016
WPX Energy No. 225H Chaco 2206-02H	30-043-21149	2-22N-6W, Sandoval	10,219	5,344	Mancos C	8/2013	59 MBO + 72 MMCFG + 3 MBW	105 MBO + 232 MMCFG + 18 MBW
Encana No. 1H Lybrook A03-2206	30-043-21130	3-22N-6W, Sandoval	9565	5,335	Mancos C	11/2012	84 MBO + 275 MMCFG + 5 MBW	144 MBO + 808 MMCFG + 14 MBW
Encana No. 1H Lybrook H03-21123	30-043-21123	3-22N-6W, Sandoval	9,870	5,397	Mancos C	5/2013	62 MBO + 245 MMCFG + 5 MBW	122 MBO + 844 MMCFG + 13 MBW
Encana No. 1H Lybrook D22-2206	30-043-21131	22-22N-6W, Sandoval	10,350	5,311	Mancos C	12/2012	27 MBO + 174 MMCFG + 25 MBW	54 MBO + 548 MMCFG + 41 MBW
Encana No. 1H Lybrook H32-2306	30-043-21126	32-23N-6W. Sandoval	12,575	5,552	Mancos C	6/2013	99 MBO + 553 MMCFG + 13 MBW	174 MBO + 95 MMCFG + 27 MBW
Encana No. 1H Lybrook I32-2306	30-043-21129	32-23N-6W, Sandoval	10,060	5,450	Mancos C	6/2013	48 MBO + 267 MMCFG + 9 MBW	92 MBO + 812 MMCFG + 22 MBW
Encana No. 2H Lybrook I32-2306	30-043-21125	32-23N-6W, Sandoval	10,204	5,434	Mancos C	6/2013	65 MBO + 253 MMCFG + 10 MBW	112 MBO + 780 MMCFG + 27 MBW
WPX Energy No. 191 H Chaco 2306-19M	30-043-21139	19-23N-6W, Sandoval	10,367	5,430	Mancos C	6/2013	56 MBO + 68 MMCFG + 7 MBW	107 MBO + 334 MMCFG + 21 MBW
Encana No. 1H Lybrook H26-2307	30-043-21118	26-23N-7W, Sandoval	9,900	5,615	Mancos C	2/2013	53 MBO + 183 MMCFG + 10 MBW	119 MBO + 741 MMCFG + 24 MBW
Encana No. 2H Lybrook H26-2307	30-043-21133	26-23N-7W, Sandoval	9,640	5,255	Mancos C	2/2013	63 MBO + 343 MMCFG + 28 MBW	101 MBO + 817 MMCFG + 77 MBW
Encana No. 1H Lybrook H36-2307	30-043-21117	36-23N-7W, Sandoval	9,985	5,607	Mancos C	3/2012	40 MBO + 115 MMCFG + 11 MBW	94 MBO + 721 MMCFG + 25 MBW

Vertical wells are drilled through the Upper Mancos Shale. In most wells, casing has been set through the entire Mancos section within the well and selected intervals are perforated. In some cases, casing has not been emplaced throughout the entire Mancos section and the productive section is left uncased, or “open-hole”.

Horizontal wells are first drilled vertically until the wellbore is just above the target zone (Mancos C). At that point the drilling curves the wellbore until it is horizontal. At that point the well is drilled horizontally. In many cases the well is drilled horizontally for a distance of approximately one mile, but the length of the horizontal segment of the well can be greater than or less than one mile. In order to obtain economically viable volumes of production in a low-permeability reservoir such as the Mancos, the reservoir must be hydraulically fractured throughout the horizontal segment of the wellbore.

Lower Mancos Shale

The Lower Mancos Shale is productive of oil and associated natural gas in northwestern Sandoval County (Fig. 15, oversize version in Appendix A). Established production is mostly confined to a narrow strip along the northernmost part of the county in T22N and T23N. In this area, production is obtained from the Semilla Sandstone in the upper part of the Lower Mancos shale. Semilla production is commingled with production from the Mancos C as well as the Upper Carlile shale, the Juana Lopez Member and sporadically from intervals in the Lower Carlile that are below the Semilla and also from the Greenhorn Limestone. Production from the Semilla, commingled with production from the Mancos C, is common to most of the Lower Mancos wells shown in Figure 15. Completion in other parts of the Lower Mancos Shale varies from well to well. Because production from multiple zones is commingled it is not possible to determine what the contribution from the individual Lower Mancos units is. However because the Semilla is the common unit to Lower Mancos production in most of the wells, it appears that it is the dominant productive unit within the Lower Mancos. Depth to the Semilla is approximately 6500 ft in the far northwestern part of the county.

The Lower Mancos has been developed by vertical wells. Small hydraulic fracture treatments have been necessary to initiate economic levels of production and have been routinely used on all Lower Mancos wells.

Dakota Sandstone

The Dakota Sandstone (Upper Cretaceous) is productive of oil and natural gas in far northwestern Sandoval County (Fig. 16, oversize version in Appendix A). In this area the Dakota is present at depths greater than 7000 ft. While production in many of the wells shown on Figure 16 is from only the Dakota, Dakota production is commingled with production from sandstones in the Graneros Shale in several of the wells. In some wells production from the Dakota is commingled with production from the Lower and Upper Mancos Shales. Almost all of the Dakota production in Sandoval County is obtained from the Lindrith West Gallup-Dakota oil pool in T22-23N, R3W. Dakota reservoirs within the Lindrith West pool consist of a series of vertically stacked sandstone bodies with the vertical seal provided by the overlying Graneros Shale (see Attebury, 1978). Although the overall perforated interval can be as thick as 150 ft, the net thickness of the sandstone reservoirs averages approximately 40 ft. Natural fractures in the Dakota sandstones appear to enhance production (Attebury, 1978). In spite of the presence of a natural fracture network, well completion involves small hydraulic fracture treatments in order to establish economic levels of production.

Figure 15. Wells that have penetrated the Lower Mancos Shale or, where the Lower Mancos is not present, older strata in Sandoval County, indicating wells productive of oil from the Lower Mancos, unproductive wells with oil shows in the Lower Mancos, and unproductive wells that have drill-stem tests or casing perforations in the Lower Mancos. Outcrop of Mancos Shale shown in green.

Lower Mancos Shale penetrations and productive wells

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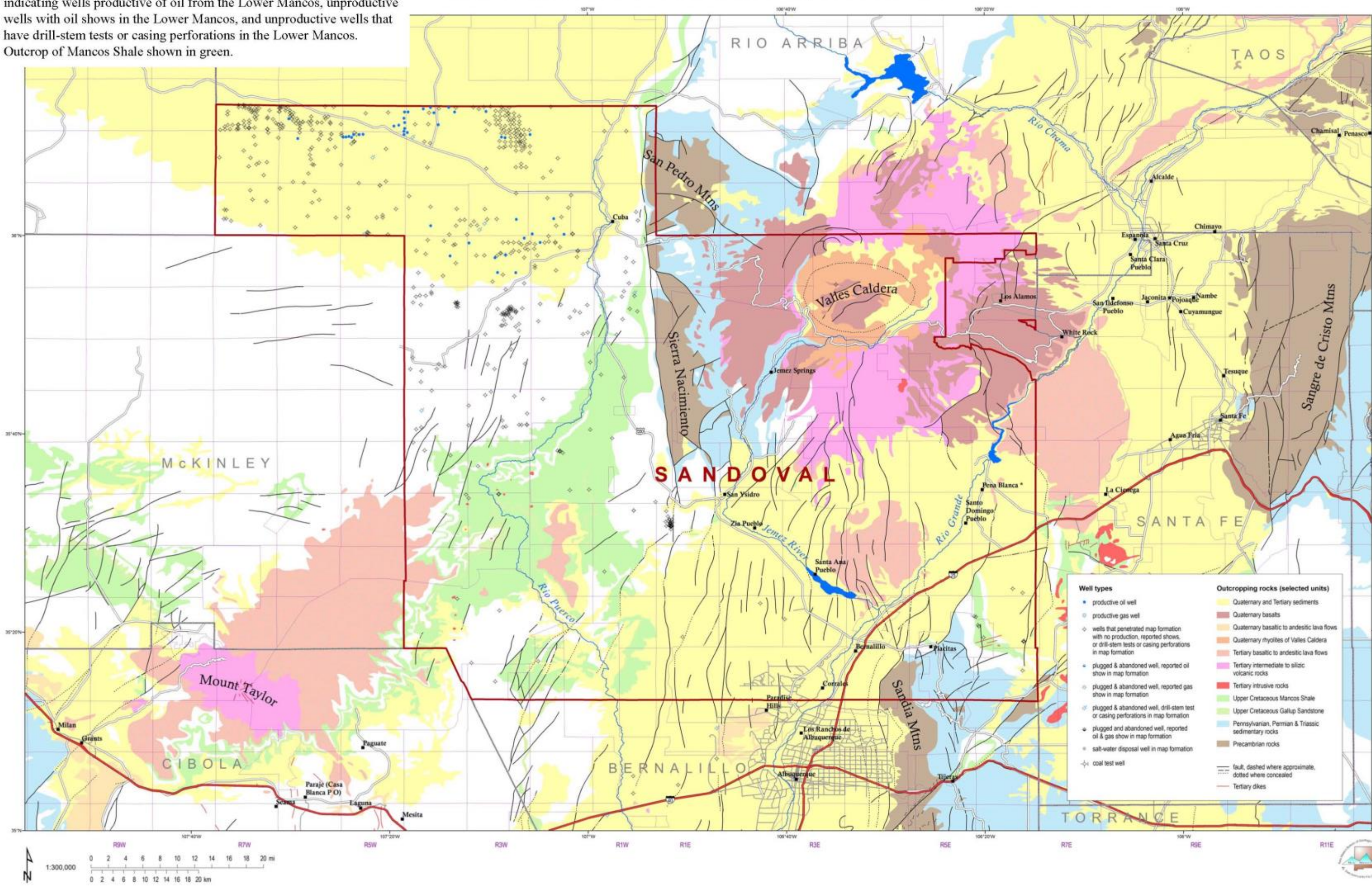
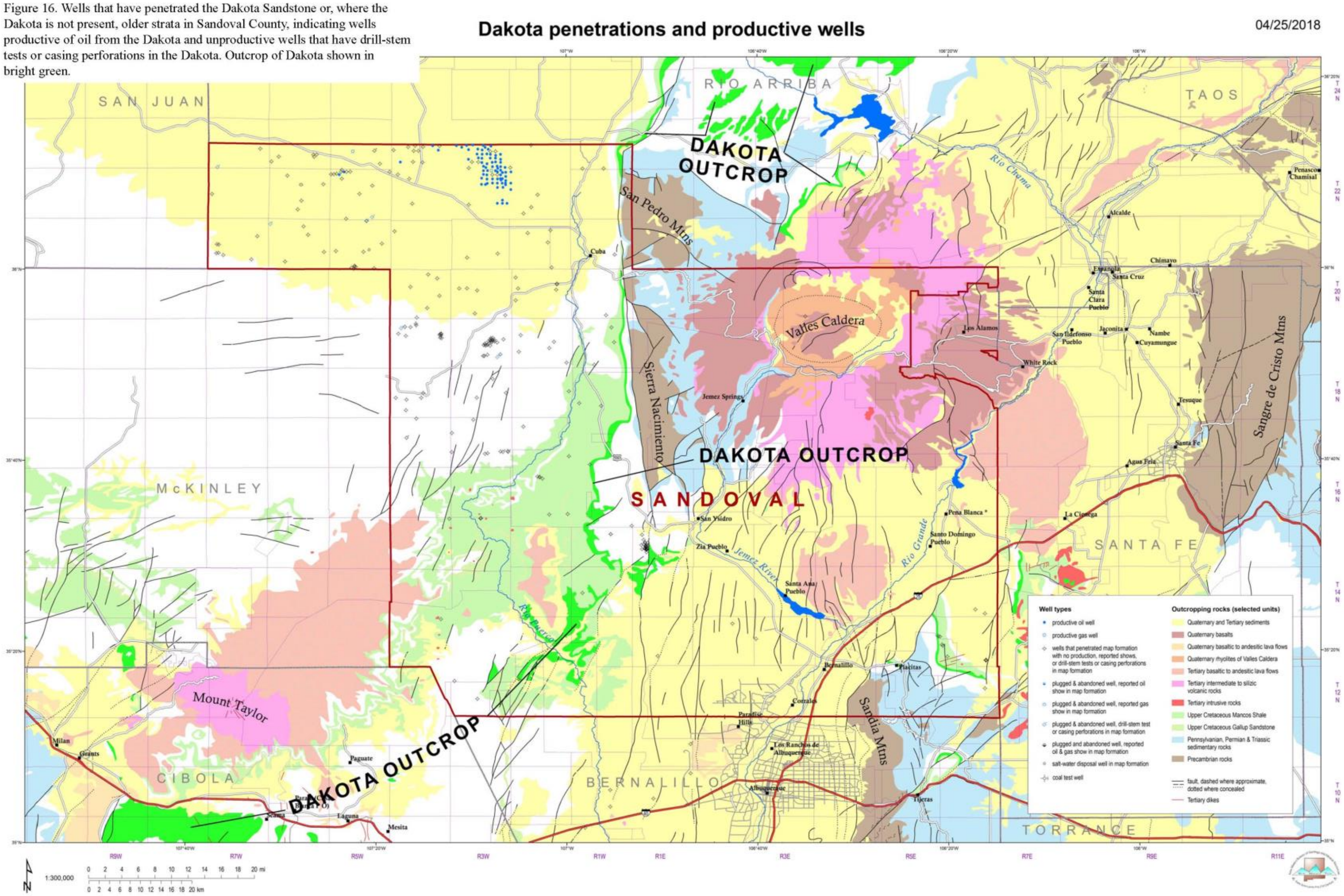


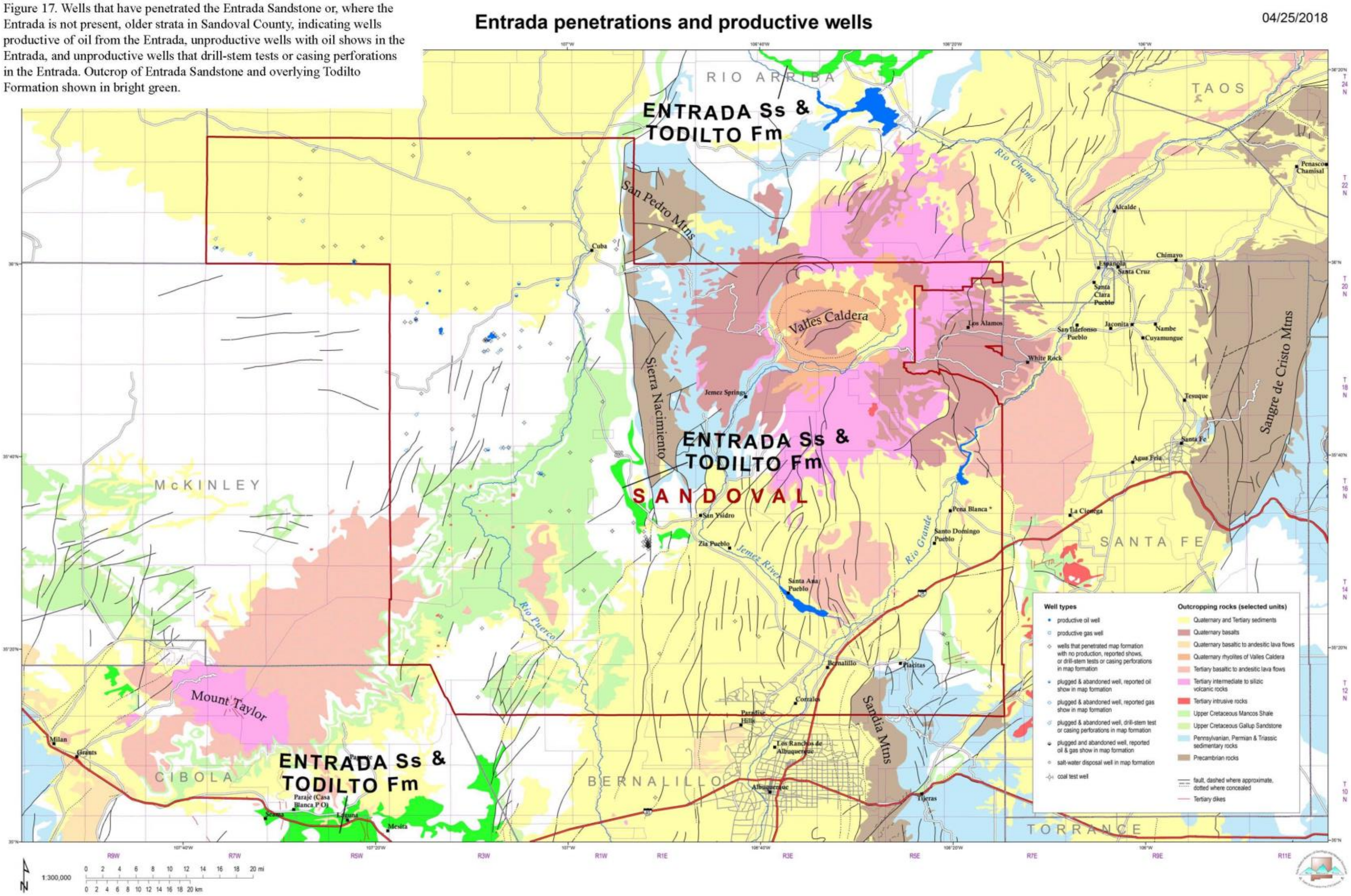
Figure 16. Wells that have penetrated the Dakota Sandstone or, where the Dakota is not present, older strata in Sandoval County, indicating wells productive of oil from the Dakota and unproductive wells that have drill-stem tests or casing perforations in the Dakota. Outcrop of Dakota shown in bright green.



Entrada Sandstone

The Entrada Sandstone (Jurassic) is productive of oil from scattered wells in northwestern Sandoval County (Figure 17, oversize version in Appendix A). Depth to the Entrada is 5400 to 5500 ft in T19N, R3-4W where most of the production occurs and deepens to approximately 8000 ft in the extreme northwestern part of the county. Oil accumulations are formed by relict sand dunes that have been preserved on the upper surface of the Entrada (Vincelette and Chittum, 1981). These relict sand dunes form four-way closure similar to that of a structural dome. The overlying limestones and anhydrites of the Todilto Formation (Jurassic) provide the vertical seal. The organic-rich Todilto limestones are the source rocks for the Entrada oil. Entrada oil is moderately light with a gravity of about 33^{o} API and Entrada permeability is high, ranging from about 200 millidarcies to about 400 millidarcies. As a result of the oil gravity and high permeability, the reservoir is completed naturally with no hydraulic fracturing needed.

Figure 17. Wells that have penetrated the Entrada Sandstone or, where the Entrada is not present, older strata in Sandoval County, indicating wells productive of oil from the Entrada, unproductive wells with oil shows in the Entrada, and unproductive wells that drill-stem tests or casing perforations in the Entrada. Outcrop of Entrada Sandstone and overlying Todilto Formation shown in bright green.



PETROLEUM SOURCE ROCKS

Major petroleum source strata within the San Juan Basin that are present within Sandoval County include the Cretaceous-age Lewis Shale, Menefee Formation and Mancos Shale as well as the Jurassic-age Todilto Limestone. In addition, the more deeply buried limestones and shales of the Madera Group are present throughout most of the county and these strata are source rocks in other parts of the San Juan Basin, especially in San Juan County where commercial oil and natural gas production has been obtained. The Lewis Shale, Menefee Formation and Mancos Shale are petroleum source rocks in the northwestern part of Sandoval County where oil and natural gas production has been established but these units lose their source capability in a southeastward direction where they become thermally immature. In the Sandoval County part of the Albuquerque Basin these strata are also mostly thermally immature although the lowermost parts of the Mancos Shale have entered the early stages of oil generation over large areas and are at optimum thermal maturity only along the basin axis. Farther south in Bernalillo County where the Albuquerque Basin is much deeper, the Cretaceous shales are within the thermogenic gas window and any generated oil has been converted into natural gas. The Todilto Limestone, being buried more deeply than the Cretaceous units is thermally mature throughout most of the county and contains oil-generative organic matter. Pennsylvanian-age strata of the Madera Group, although long suspected to contain petroleum source rocks and thermally mature where it is present in the county contains insufficient organic matter to function as a major source rock. Other strata including the Tertiary section in the Albuquerque Basin, the Jurassic-age Morrison Formation, the Triassic-age Chinle Formation, and the Permian-age Yeso and Abo Formations contain insufficient organic matter to act as source rocks. In summary, petroleum source rocks are present in the Cretaceous section in northwestern Sandoval County but these same strata lose their thermal maturity and do not function as source rocks elsewhere in the county. The Todilto Limestone is a thermally mature source rock that has generated oil over most of the area where it is present in the county. Pennsylvanian strata in the deepest part of the sedimentary section are thermally mature but contain insufficient organic matter to function as petroleum source rocks. A more detailed analysis and discussion of major source rock units follows. Supporting data in the form of specialized source rock analyses on drill core and well cuttings are given in the Sandoval County source rock database (***sandovalsrcrks.xls*** in Appendix B).

Lewis Shale

The Lewis Shale is the uppermost (shallowest) major Cretaceous shale unit within the San Juan Basin. Present at depths of approximately 2,000 ft in the northwestern most part of the county it rises steadily to the southeast until it is exposed at the ground surface and truncated by erosion at the outcrop just a few miles south of Cuba (Figures 4, 11, oversize versions in Appendix A). In the Albuquerque Basin in the south-central part of the county, the Lewis is present at various depths in most of the deeper fault blocks (cross sections, Figures 4, 5, oversize versions in

Appendix A). Although petroleum source rock data are not available for the Lewis in the northwestern part of Sandoval County, the presence of commercial gas wells that are completed in the Chacra section indicates that the Lewis has sufficient Total Organic Carbon (TOC) and is sufficiently mature to have generated gas in that area. Dube and others (2000) indicate that TOC contents of Lewis shales elsewhere in the San Juan Basin range from 0.45% to 1.5% and average approximately 1.0%, which is not especially high but is sufficient for petroleum generation. There is only one analysis of organic matter type available from the Lewis Shale. That analysis is from the Shell No. 1 Santa Fe well located in the Sandoval County part of the Albuquerque Basin (see cross section B-B', Figure 4 in Appendix B). In that sample, the visual kerogen analysis and the Rock-Eval pyrolysis indicate the organic matter is a mixture of oil-prone types, gas-prone types, and non-generative inertinites.

Although the Lewis is almost certainly thermally mature in the northwestern part of the county, it almost certainly becomes thermally immature, and therefore nongenerative, to the southeast as the outcrop belt is approached because the deeper Mancos shales are immature in this area. Within the Shell No. 1 Santa Fe well in the Albuquerque Basin, the Lewis is thermally immature with a Thermal Alteration Index of only 1.5 so that all that can be hoped for is a low-grade resource of biogenic gas in this part of the Albuquerque Basin. The U.S. Geological Survey thermal model of the Shell No. 1 Santa Fe well as well as the Shell No. 3 Santa Fe well also indicate that the Lewis Shale is thermally immature and therefore essentially nongenerative in this northern, shallow part of the Albuquerque Basin (see Johnson et al., 2001).

Menefee Formation

The Menefee Formation, with its interbedded nonmarine shales, coals and sandstones, is a source rock for small oil reservoirs in Menefee sandstones in the northwestern part of Sandoval County (Figure 12, oversize version in Appendix A). In the northwestern part of Sandoval County the Menefee lies at a depth of 3,500 to 4,100 ft and has been matured into the upper part of the oil window. Despite the relatively low level of thermal maturity, oils are light with API gravities in the 40-46^{o} range. As with the overlying Lewis shales, the Menefee gradually rises to the southeast until it is truncated at the outcrop belt approximately 10 miles south of Cuba and becomes thermally immature as with the underlying Mancos Shale. As with the Lewis, the Menefee has been removed by erosion from the southwestern part of Sandoval County as well as from the Sierra Nacimiento and much of the eastern part of the county and from the Sandia Mountains in the southeast. In the Albuquerque Basin in the south-central part of Sandoval County, the Menefee is present at varying depths in the different fault blocks (Cross section B-B', Figure 5 in Appendix A). In the Shell No. 1 Santa Fe well it is present at depths of 3600 to 4400 ft and is thermally immature with a vitrinite reflectance (R_o) value of only 0.50 and a Thermal Alteration Index of only 1.5, indicating that it has not generated significant volumes of oil or natural gas in the Sandoval County part of the Albuquerque Basin. The U.S. Geological

Survey thermal modeling of the Shell No. 1 Santa Fe well and the Shell No. 3 Santa Fe well (Johnson et al., 2001) also indicates that the Menefee is thermally immature and nongenerative in the Sandoval County part of the Albuquerque Basin. Further south in Bernalillo County where the basin is much deeper, the U.S. Geological Survey thermal modeling indicates that the Menefee is within the thermogenic gas zone and that any oil that may have been generated has been thermally broken down into natural gas (Johnson et al., 2001).

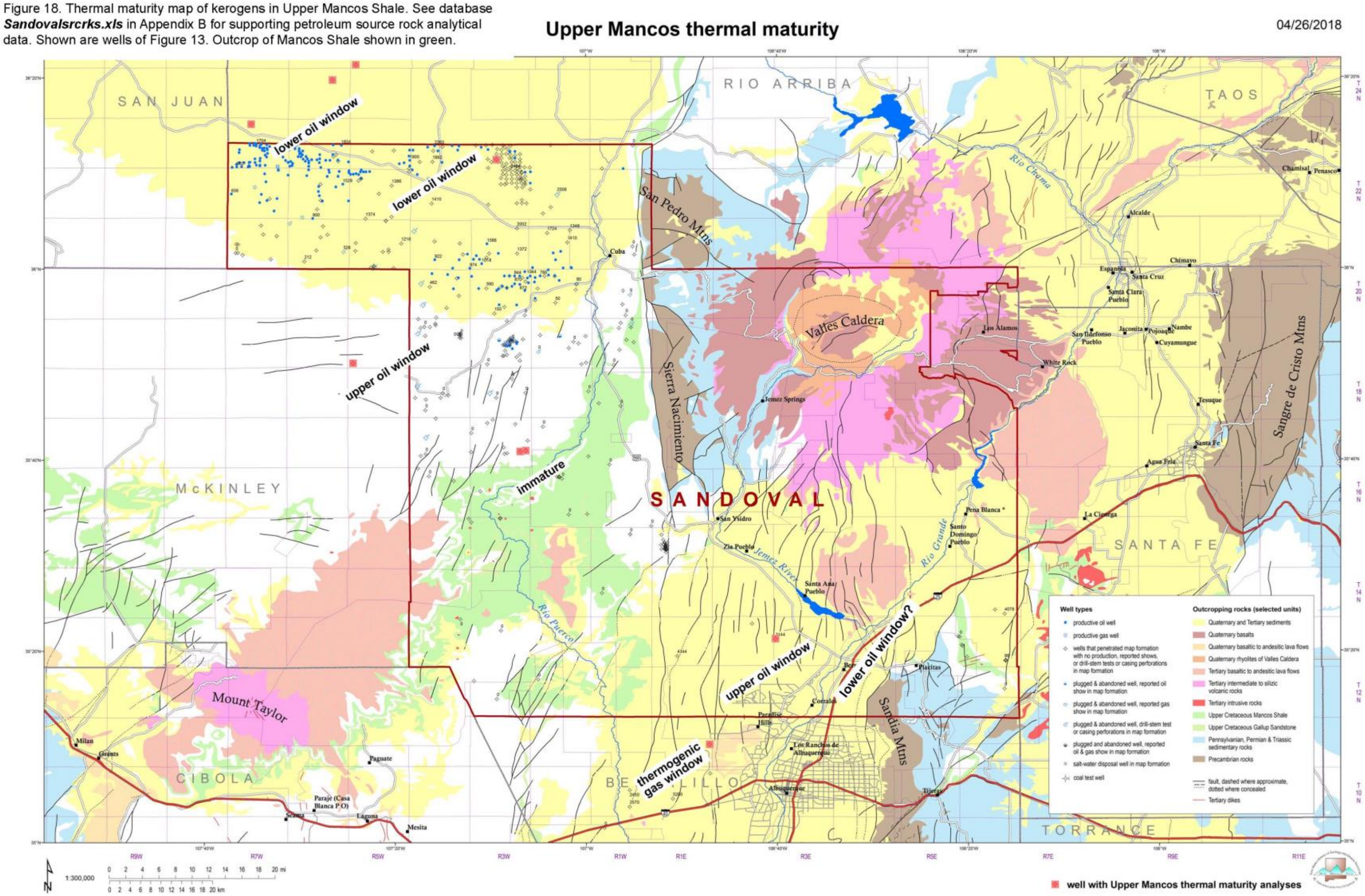
Upper Mancos Shale

The Upper Mancos Shale is the major oil producing stratigraphic unit in the San Juan Basin. Most Mancos production in the San Juan Basin has been obtained from the Mancos C. In Sandoval County the Mancos C is the major oil-productive unit of all stratigraphic units, including those shallower and deeper than the Mancos. Recent and current shale exploration has been focused on the Mancos C (Broadhead, 2015). Oil is produced from the Mancos C mainly in the northwestern part of the county with only a subsidiary amount of production obtained from central part of the county (Figure 13, oversize version in Appendix A). As such, evaluation of the petroleum source rock properties of the Upper Mancos Shale is critical to the assessment of the oil and natural gas potential of Sandoval County.

The Upper Mancos Shale in northwestern Sandoval County and adjoining areas of Rio Arriba and San Juan Counties is thermally mature (Figure 18, oversize version in Appendix A) and contains more than sufficient organic matter to have generated substantial amounts of oil and natural gas. TOC is generally in the 1% to 3% range. Thermal maturity is in the lower part of the oil window with R_o values of 0.85% to 1.0% in the Mancos C and somewhat less, 0.75% to 0.87% in the shallower Mancos B. This places the shales in the Mancos C at a maturity level at or near peak oil generation. Furthermore, the organic matter within the Mancos C in northwestern Sandoval County is oil prone so that oil and associated gas would have been generated upon maturation. These source rock characteristics, combined with the established Mancos C production, provide a base to compare the Mancos C source rocks in the productive part of Sandoval County with the Mancos C source rocks elsewhere in the county.

Similar to the shallower Cretaceous source rocks, the Mancos C becomes shallower as one moves to the southeast before it is truncated by erosion and absent south of its outcrop belt approximately 15 miles south of Cuba. In the Shell No. 1 41 Wright well, located 10 miles south of the southernmost Upper Mancos production, the Mancos C is thermally immature with a Thermal Alteration Index of only 1.6. In between the area of immaturity and the area matured to the lower oil window is an area where maturation has been into the upper oil window. This is seen in the Dunigan No. 1 Santa Fe well which is located in Sec. 31, T19N, R5W in northeastern most McKinley County. In that well, TMAX in the Mancos B and Mancos C ranges from 429^o to 435^o, indicating maturation into the upper oil window. Although data are somewhat limited, the

Figure 18. Thermal maturity map of kerogens in Upper Mancos Shale. See database ***Sandovalsrcrks.xls*** in Appendix B for supporting petroleum source rock analytical data. Shown are wells of Figure 13. Outcrop of Mancos Shale shown in green.



southeast limit of Mancos C production appears to occur in the area of maturation into the upper oil window, although most Mancos production occurs down dip to the northwest where the Upper Mancos Shale has been matured into the lower oil window. Thus far, all horizontal Mancos C oil wells have been drilled in the far northwestern part of the county where the Mancos C has reached optimum thermal maturity in the lower part of the oil window.

The Mancos C is present within the Sandoval County part of the Albuquerque Basin. In the Shell No. 1 Santa Fe well the Mancos C is present between depths of 5430 ft to 5700 ft (Cross section B-B', Figure 5 in Appendix A). Although no thermal maturity measurements are available for the Mancos C in this well, the overlying Mancos B and the underlying Upper Carlile shale and Juana Lopez Member of the Lower Mancos Shale are at the boundary between thermal immaturity and the uppermost part of the upper oil window with R_o values of 0.49 to 0.60, Thermal Alteration Index values of 2.15 to 2.2, and Rock-Eval TMAX values ranging from 430^o and 432 ^{o}. Therefore, the Mancos C has only just begun to generate oil in this northern, shallow part of the Albuquerque Basin. The U.S. Geological Survey thermal modeling of the Shell No. 1 Santa Fe well and the Shell No. 3 Santa Fe well (Johnson et al., 2001) indicates that the Upper Mancos Shale is thermally immature and has not generated significant amounts of hydrocarbons. Johnson and others (2001) underestimated thermal maturity compared to the maturity presented in this report which is based on “hard” analyses of drill cuttings from the Shell No. 1 Santa Fe well. Neither the U.S. Geological Survey analysis nor the analysis provided for this report places the Mancos C at optimum thermal maturity over large portions of the Sandoval County part of the Albuquerque Basin. Therefore the two assessments of thermal maturity are in general agreement. Along the basin axis, which approximately coincides with the Rio Grande, Connells' (2008) cross section A-A' suggest that the Mancos C may occur at depths approximately 7500 ft deeper than in the Shell No. 1 Santa Fe well. This would place the Mancos C either in the lower part of the oil window at or near peak oil generation or within the thermogenic gas window where previously generated oil would have been thermally cracked to gas. Further south in Bernalillo County where the basin is much deeper, the U.S, Geological Survey thermal modeling indicates that the Upper Mancos Shale is within the thermogenic gas zone and that any oil that may have been generated has been thermally broken down into natural gas (Johnson et al., 2001).

Lower Mancos Shale

The Lower Mancos Shale is a significant petroleum source rock in northwestern Sandoval County where it lies at depths of 5,500 ft to 6,200 ft. As it rises out of the San Juan Basin its constituent members extend farther south than those of the overlying Cretaceous strata (Cross section A-A' Fig. 4, oversize version in Appendix A). The Lower Mancos Shale is present over much of the southwestern part of the county where its constituent members form the rock outcrop over most of this area. To the southeast in the Sandoval County part of the

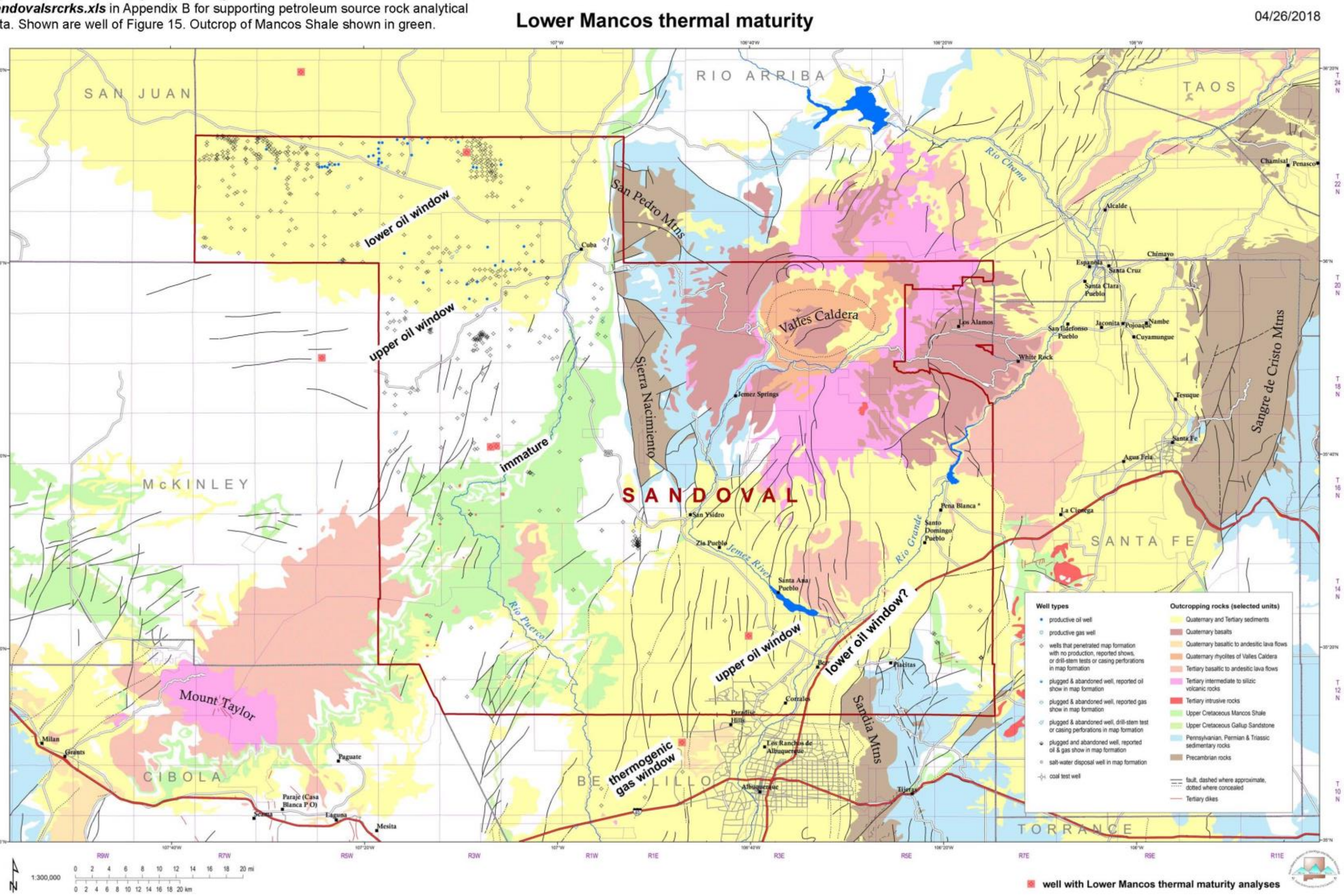
Albuquerque Basin, the Lower Mancos is present at varying depths in the different fault blocks and its top is at 7,800 ft in the Shell No. 3 Santa Fe well and is shallower at 5,700 ft further to the east in the Shell No. 1 Santa Fe well (Cross section B-B' Figure 5, oversize version in Appendix A). Farther to the east the Lower Mancos has been eroded from the Sandia Mountains uplift but is preserved northward as this mountainous uplift plunges into the subsurface.

Shales in the Lower Mancos have more than sufficient organic matter to have generated oil and natural gas with TOC values generally between 1.5 and 2.0%. The Rock-Eval Hydrogen Index and Oxygen Index values obtained from source rock analyses indicate that the organic matter is a mixture of oil-prone and gas-prone types with oil-prone types dominating, which is expected given the marine depositional environment of the shales.

Thermal maturity of the Lower Mancos in northwestern Sandoval County is within the lower part of the oil window (Figure 19 in Appendix A) with R_o values in the 0.8 to 0.9% range. This indicates that the source rocks are at or near peak oil generation. Toward the southeast as the Lower Mancos rises out of the San Juan Basin and approaches its outcrop belt , the Lower Mancos shales become thermally immature (and therefore nongenerative) with a Thermal Alteration Index of only 1.8, a Rock-Eval TMAX of 430^o, and a Rock-Eval Productivity Index of only 0.03.

In the Albuquerque Basin in south-central Sandoval County, the Lower Mancos Shale has been matured to the uppermost part of the oil window. In the Shell No. 1 Santa Fe well, the Thermal Alteration Index is 2.2, R_o ranges from 0.49 to 0.65, and Rock-Eval TMAX is 432^o . Therefore these shales have only begun to generate oil and peak oil generation has not yet been attained. The U.S. Geological Survey thermal modeling of the Shell No. 1 Santa Fe well and the Shell No. 3 Santa Fe well (Johnson et al., 2001) indicates that the Lower Mancos is thermally immature and therefore nongenerative. The thermal model therefore somewhat underestimates the maturity presented in this report which is based on "hard" analyses of well cuttings from the Shell No. 1 Santa Fe well. Neither the U.S. Geological Survey analysis nor the analysis provided for this report places the Lower Mancos at optimum thermal maturity over large portions of the Sandoval County part of the Albuquerque Basin. Similar to the Mancos C, the Lower Mancos may be within either the lower part of the oil window or within the thermogenic gas window along the axis of the Sandoval County part of the Albuquerque Basin, which approximately coincides with the Rio Grande. Therefore the two assessments of thermal maturity are in general agreement. Further south in Bernalillo County where the basin is much deeper, the U.S. Geological Survey thermal modeling indicates that the Lower Mancos is within the thermogenic gas zone and that any oil that may have been generated has been thermally broken down into natural gas (Johnson et al., 2001).

Figure 19. Thermal maturity map of kerogens in Lower Mancos Shale. See database ***Sandovalsrcrks.xls*** in Appendix B for supporting petroleum source rock analytical data. Shown are well of Figure 15. Outcrop of Mancos Shale shown in green.



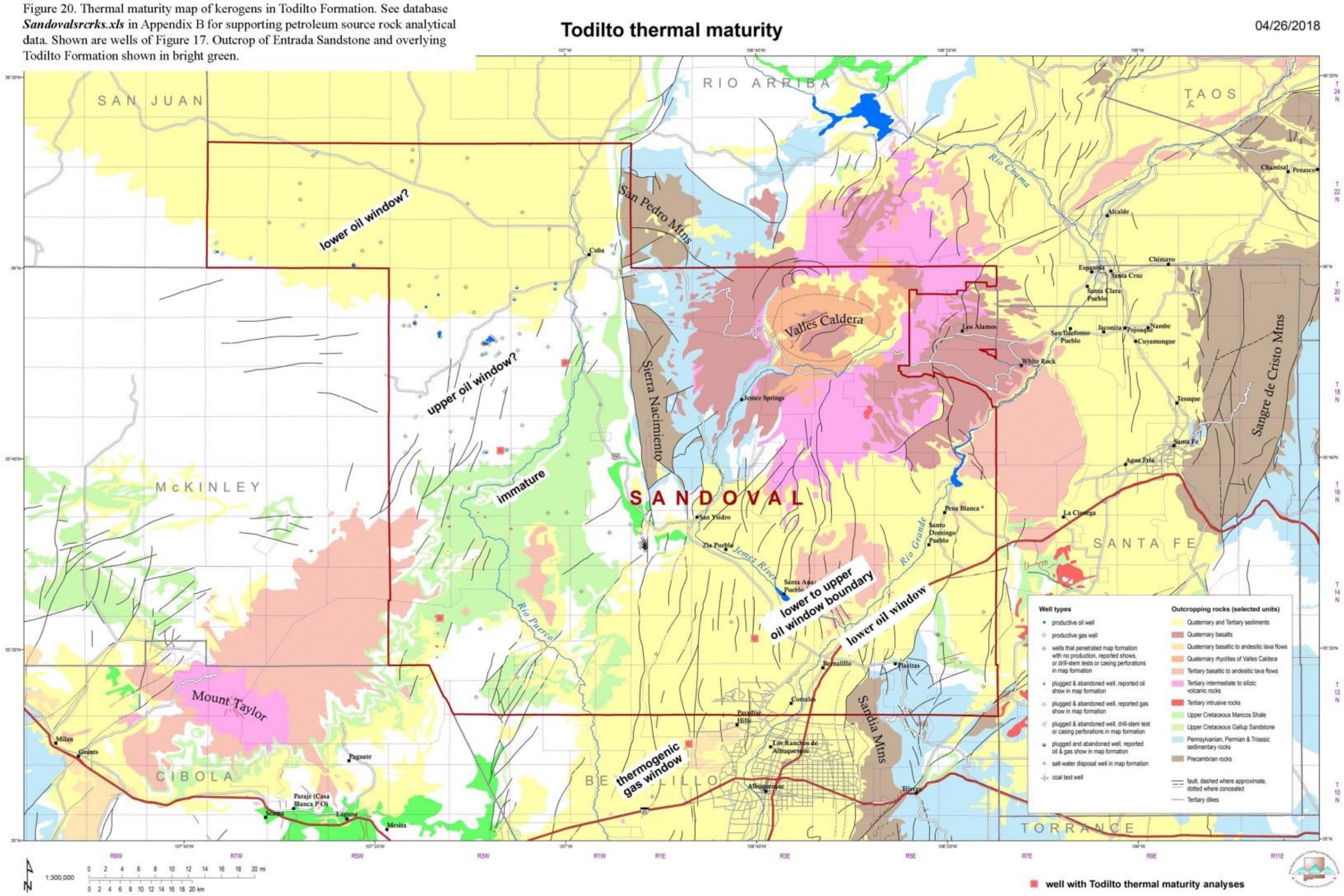
Todilto Limestone

The organic-rich lacustrine Jurassic-age Todilto limestones have long been regarded as the petroleum source rocks for oil trapped in the underlying Entrada Sandstone (Vincelette and Chittum, 1981). With TOC in the 1% to 3% range in Sandoval County, the Todilto contains more than sufficient organic matter to function as a source rock. Todilto organic matter is predominantly oil prone which would have generated oil and associated gas upon maturation.

Although no petroleum source rock analyses are available for northwestern Sandoval County or adjoining parts of Rio Arriba and San Juan Counties, the Todilto is presumably thermally mature within this area because the shallower Cretaceous strata are thermally mature and are within the lower part of the oil window. Therefore, it would seem that the Todilto has been matured to peak oil generation. However, thermal maturity decreases to the southeast as the Todilto rises out of the San Juan Basin (Figure 20, oversize version in Appendix A). In the Shell Oil No. 41 Wright well in Sec. 26, T17N, R3W, the Todilto appears to be thermally immature with a Thermal Alteration Index of 2.0, a relatively low TMAX of 432^o and a low Rock-Eval Productivity Index of 0.02. To the northeast in the El Paso Natural Gas No. 1 Elliott State well in Sec. 34, T19N, R2W maturity parameters are similar with a Thermal Alteration Index of 2.0, a TMAX of 426^o, and a Productivity Index of 0.05. To the southwest in the Continental No. 1 L-Bar well in Sec. 2, T13N, R4W the sparse data also suggest thermal immaturity with a TMAX of only 425^o.

In the Shell No. 1 Santa Fe well in the Sandoval County part of the Albuquerque Basin, the Todilto is thermally mature and near the boundary between the upper and lower parts of the oil window with an R_o of 0.69, a TMAX of 440^o, and a Productivity Index of 0.25, although the Thermal Alteration Index at 1.8 suggests immaturity. The Rock-Eval Hydrogen Index at 41 mg hydrocarbons/g organic carbon and Oxygen Index at 11 mg CO_2/g organic carbon indicate a mature source rock. The Todilto will be thermally more mature along the axis of the basin under the Rio Grande. Further south in Bernalillo County where the basin is much deeper, the U.S. Geological Survey thermal modeling indicates that the Todilto is within the thermogenic gas zone and that any oil that may have been generated has been thermally broken down into natural gas (Johnson et al., 2001).

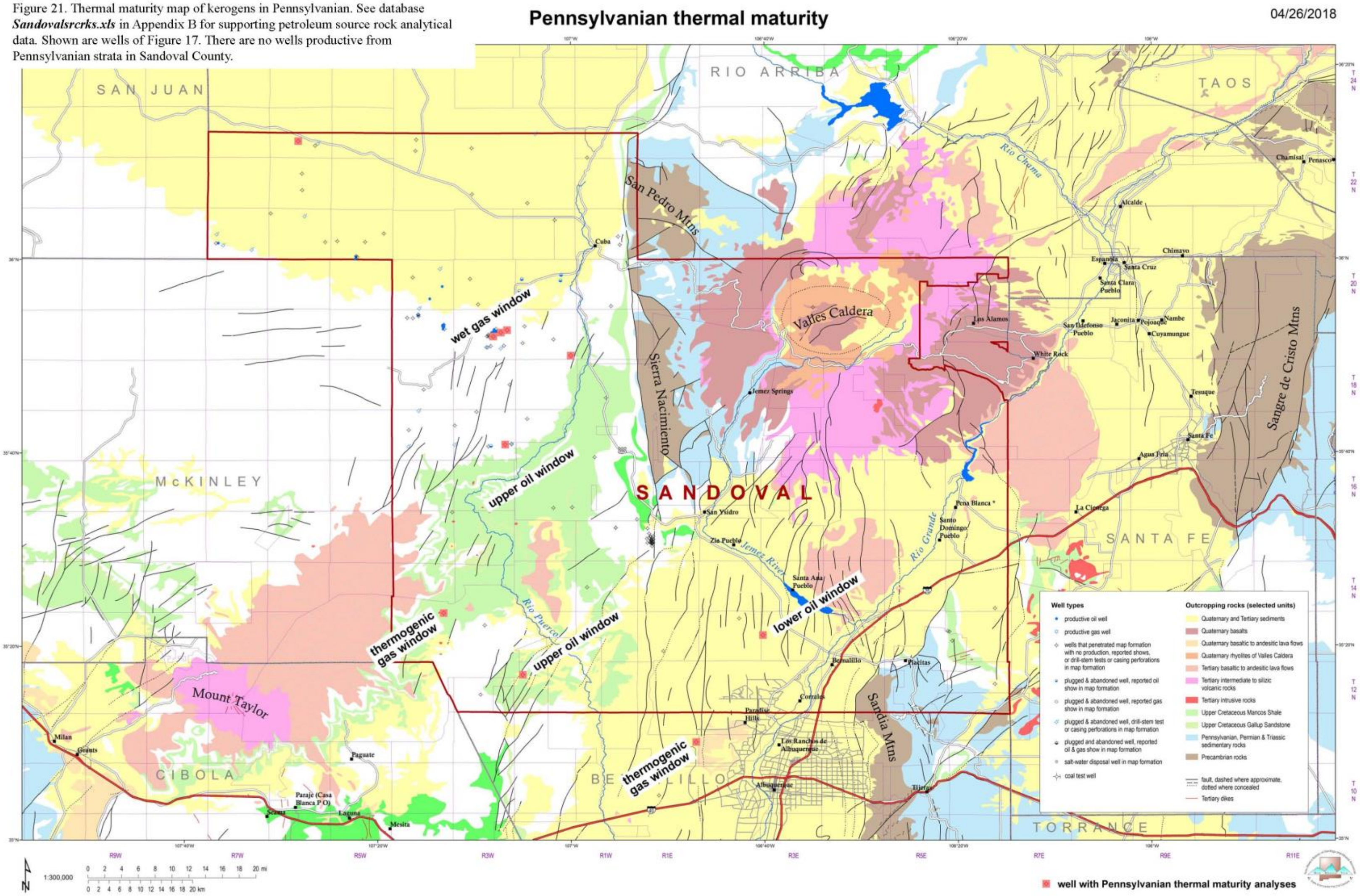
Figure 20. Thermal maturity map of kerogens in Todilto Formation. See database ***Sandovalsrcrks.xls*** in Appendix B for supporting petroleum source rock analytical data. Shown are wells of Figure 17. Outcrop of Entrada Sandstone and overlying Todilto Formation shown in bright green.



Pennsylvanian strata

Pennsylvanian strata, consisting of marine limestones and red shales with minor gray shales and sandstones have long intrigued geologists as potential source rocks in Sandoval County and adjacent areas. Therefore, numerous petroleum source rock analyses have been performed on samples of well cuttings from several wells in the county. These analyses reveal that significant source rocks are not present within the Pennsylvanian section in Sandoval County. Thermal maturity is favorable and ranges from the oil window to the wet gas window in the northwestern and central parts of the county (Figure 21, oversize version in Appendix A). Further south it is within the upper part of the oil window. In the Sandoval County part of the Albuquerque Basin the Pennsylvanian is within the lower part of the oil window and the stage of peak oil generation has been attained. Further south in Bernalillo County where the basin is much deeper, the U.S. Geological Survey thermal modeling indicates that the Pennsylvanian is within the thermogenic gas zone and that any oil that may have been generated has been thermally broken down into natural gas (Johnson et al., 2001). However, Pennsylvanian strata are organically poor and most strata do not contain more than 0.3% TOC. Furthermore, the types of organic matter present are a mixture of oil-prone, gas-prone, and inertinitic types. With the presence of a large inertinitic fraction, the amount of organic carbon that is capable of petroleum generation is even less than 0.3%. A substantial amount of gas-prone organic matter within the remaining generative fraction essentially eliminates the possibility of any significant oil generation. Although it is possible that thick beds of organic-rich gray shales which might act as source rocks are present, they have not been identified in the subsurface of Sandoval County and therefore cannot at this time be considered to be present.

Figure 21. Thermal maturity map of kerogens in Pennsylvanian. See database ***Sandovalsrcrks.xls*** in Appendix B for supporting petroleum source rock analytical data. Shown are wells of Figure 17. There are no wells productive from Pennsylvanian strata in Sandoval County.



PETROLEUM (Oil & Natural Gas) POTENTIAL

The oil and natural gas potential of Sandoval County varies from nil to high. The potential varies across the county with some parts of the county having little or no oil and gas potential because of an absence of petroleum source rocks and/or reservoirs, source rocks that are thermally immature, an absence of petroleum traps, or extensive volcanism. Within areas that have potential, the potential will vary with depth because of variations is source rocks, reservoirs, and trapping characteristics of strata of different ages. This section discusses the petroleum potential of five subdivisions of the county: 1) the mountain ranges; 2) the northeast; 3) the northwestern and west-central part of the county; 4) the southwestern part of the county; and 5) the Albuquerque Basin.

The Mountain Ranges: Sierra Nacimiento, San Pedro Mountains, Sandia Mountains

The oil and natural gas potential of the Sierra Nacimiento, San Pedro Mountains, and Sandia Mountains is very low to zero. On the crests of these mountain ranges, Precambrian basement is exposed at the surface. The Precambrian contains neither reservoir rocks nor source rocks. On the eastern, northern and southern flanks of these mountain ranges, Pennsylvanian, Permian, Triassic and Jurassic strata are exposed and dip into the adjacent basinal areas. Exposure of these strata on the uplift flanks has destroyed any traps that may have been present. Furthermore as presented in the discussion of the northwestern and west-central areas, only the limestones of the Todilto Formation (Jurassic) contain any significant petroleum source rocks so that oil and natural gas were not generated in any of the other stratigraphic units present on the flanks of the mountain ranges.

Northeastern Sandoval County (Jemez Mountains volcanic field and Valles Caldera)

The northeastern part of Sandoval County has very low oil and gas potential. Although this part of the county has remained undrilled except for geothermal exploration wells in the Valles Caldera area, the general geologic setting suggests a very low potential. Although strata of Cretaceous and Jurassic age that have both source rocks and reservoirs may be present in places in the subsurface of the northeastern part of the county, the limited available data indicate that they have been removed by Laramide erosion under the western part of the Jemez Mountains volcanic field (Goff et al., 2011; Goff and Goff, 2017). It is possible that petroleum source rocks are present within the Pennsylvanian section, although the Pennsylvanian appears to contain insufficient organic matter for petroleum generation elsewhere in the county. However, the intense heat associated with Tertiary and Quaternary volcanic activity and accompanying pervasive magmatic intrusion would have acted to naturally crack any generated oil into natural gas. Furthermore, the rising magmas would have exsolved volcanic gases, which primarily consist of water and carbon dioxide. The carbon dioxide, once exsolved from the magmas, enters the reservoirs and dilutes any hydrocarbon gases that may be present. This results in the occurrence of low-BTU gases which generally contain insufficient hydrocarbons to be produced commercially (*low-BTU gases are those that have a low heat output upon burning because a significant percentage of the components are not flammable)*. If no hydrocarbons have been generated within the Pennsylvanian section because of an absence of petroleum source rocks, it is possible that CO_2-rich gases are present in Triassic, Permian or Pennsylvanian reservoirs under the volcanic field. Reservoirs that are not associated with petroleum source rocks (the Pennsylvanian, Abo, Yeso, Glorieta, Triassic, and Morrison) may contain gases that are nearly pure carbon dioxide. This has occurred in strata of the Raton Basin of north-central New Mexico that contain no petroleum source rocks (see Broadhead, 2012).

Northwestern and west-central Sandoval County (San Juan Basin and northeastern part of transition to Albuquerque Basin)

This area encompasses that part of Sandoval County west of the main fault that delineates the west side of the Sierra Nacimiento and the San Pedro Mountains. The area forms the southeastern part of the San Juan Basin. All of the established oil and natural gas production in the county is located within this area. The oil and gas potential of each stratigraphic unit within northwestern and west-central Sandoval County is discussed below, beginning with the shallowest (youngest) strata and ending with the deepest (oldest) strata.

Tertiary-age strata

The San Jose Formation, Nacimiento Formation, and Ojo Alamo Sandstone constitute the Tertiary stratigraphic section in northwestern Sandoval County. These strata are successively truncated to the south and east by the present-day land surface as they rise out of the San Juan Basin (Cross section A-A' Figure 4, oversize version in Appendix A). The Nacimiento Formation consists of light-gray to black lacustrine shales and minor, discontinuous fluvial sandstones. These sandstones have produced small volumes of gas from small gas pools located near the eastern edge of the San Juan Basin. None of these gas accumulations is located within Sandoval County. The closest one is the Gavilan Nacimiento gas pool, located in Se. 6, T24N, R1W and Sec. 12, T24N, R2W, 10 miles north of the Sandoval-Rio Arriba county line. Spurious accumulations of gas in Nacimiento sandstones may be found in far northwestern Sandoval County. The lenticular geometries of Nacimiento sandstones as well as the shallow depths, that result in low reservoir pressures, indicates any reserves that may be present will be small and therefore not likely to be developed.

Fruitland Formation (Upper Cretaceous)

The Fruitland Formation is productive of coalbed methane in northwestern Sandoval County (Figure 9, oversize version in Appendix A). Where production occurs in T21N, R6-7W, it coincides with the greatest net thickness of coal beds within the Fruitland (see Ayers and Ambrose, 1990; Ayers et al., 1994). Other areas characterized by maximum net coal thickness of more than 30 ft are present along the northern border of the county in T22-23N, R3-5W. South and east of these areas, net thickness of coal decreases which will result in a decrease in coalbed methane potential. Potential is ultimately limited to the southeast by the southeastern outcrop of the Fruitland Formation. Another factor, besides a decrease in coal thickness, that limits potential to the south and east is the decreased depth to the Fruitland as it rises towards its outcrop at the surface (see Cross section A-A' in Appendix A). As the Fruitland coals become shallower, the hydraulic head of water in the cleat system decreases which results in decreasing reservoir pressures. The volume of gas adsorbed onto the coals will decrease with the decreasing hydraulic pressure in the cleats and will therefore decrease with decreasing depth of the coal reservoir.

Pictured Cliffs Sandstone (Upper Cretaceous)

The current outlines of the two Pictured Cliffs gas pools, Ballard and Blanco South, that enter the county from the north (Figure 10, oversize version in Appendix A) reflect the trend of the maximum thickness of pay sandstone in the Pictured Cliffs (see Brown, 1978a, 1978b). These trends of maximum pay thickness are defined by the central trend of the Pictured Cliffs coastal barrier sands. Although some exploratory wells have tested the Pictured Cliffs and recorded shows south of the Ballard and Blanco South pools, production is unlikely in these areas because of the pinchout of the barrier sandstones into back-barrier shales (see Whitehead, 1993; Reese, 1955). The present distribution of Pictured Cliffs gas wells in Sandoval County reflects maximum or near-maximum development of the gas resource in this stratigraphic unit. Production to the southeast will be limited not only by the limited extent of the coastal barrier sandstones but also by decreasing thermal maturity of source rocks in the overlying Fruitland Formation and the underlying Lewis Shale due to decreasing burial depth to the southeast. The southeastern outcrop belt of the Pictured Cliffs, which cuts through T19N, R3-4W (see cross section A-A' Figure 4, oversize version in Appendix A) limits the presence of Pictured Cliffs sandstones to northwestern Sandoval County.

Lewis Shale (Upper Cretaceous)

The Chacra sandstones, which are present in the upper part of the Lewis Shale, are the productive Lewis reservoirs in Sandoval County (Figure 11, oversize version in Appendix A). The resource in the Chacra is gas, not oil. The area of potential within the Chacra is confined to that part of the county northwest of the outcrop belt of the Lewis Shale. The current pattern of productive wells appears to coincide with the distribution of sandstones with optimal reservoir quality in the Chacra. The presence of scattered productive gas wells northeast and southwest of the main productive trend suggests that the maximum productive boundaries of the Chacra have not yet been reached. Although numerous wells have penetrated the Chacra northeast and southwest of the main productive trend, most of these wells have targeted deeper oil zones, primarily in the Mancos Shale and should not be regarded as Chacra tests.

Menefee Formation (Upper Cretaceous)

The Menefee Formation is productive of oil from small scattered accumulations in northwestern and west-central Sandoval County (Figure 12, oversize version in Appendix A). Reservoirs are isolated fluvial sandstone bodies encased in paludal (swamp) shales. Lenticular coal beds are also present. The encasing shales are almost certainly the source rocks as well as the seals for the sandstone reservoirs. In areas between the established fields, scattered wells have tested the Menefee without establishing production. Most of the dry holes in the northwestern and west-central parts of the county have targeted deeper strata and cannot be considered Menefee tests.

The known Menefee oil pools are formed by narrow channels less than ¼ mile wide (see Higgins, 1983a). Traps are either stratigraphic or combination structural-stratigraphic. The limited area where sandstones are deposited in a meandering fluvial system severely limits the size of the oil pools that may be found in the Menefee. Therefore, exploration for undiscovered Menefee oil will be difficult. Detailed subsurface mapping using wells that have penetrated the Menefee combined with reflection seismic surveys may help. Area of potential will be limited to areas north and west of the Menefee outcrop belt (Cross section A-A' Figure 4, oversize version in Appendix A). Because production has been obtained near the outcrop belt and at shallow depths of 330 ft at the San Luis South oil pool, it appears that the entire area north and west of the Menefee outcrop belt may be prospective, although the actual productive area will be limited to small Menefee sandstones bodies within this area.

Upper Mancos Shale

The Upper Mancos Shale is the most extensive oil-producing unit in northwestern and west-central Sandoval County (Fig. 13, oversize version in Appendix A). As previously discussed, production is primarily from the sandstone-bearing Mancos C unit. Because of the low permeability of the thin sandstone beds in the Mancos C and because of the lenticular nature of individual sandstone beds, oil and gas migration distances are short. Therefore, oil will be found in areas close to where it has been generated and will not migrate updip very far. Also, in low-permeability unconventional reservoirs such as the Mancos C, optimum oil production in any particular shale unit will take place where thermal maturation has proceeded into the lower part of the oil window. Peak oil generation is obtained where vitrinite reflectance is in the 0.9% to 1.0% range (Hunt, 1996; Huc, 2013; Merrill, 1991). Although oil will begin to be generated at vitrinite reflectance values of approximately 0.6%, larger volumes of oil will be generated as the source rock attains peak oil generation. Consequently, production will be greater in areas where the shale is more mature. Using the example from the Woodford Shale (Devonian) of Oklahoma (Cardott, 2014), although the lowest thermal maturity associated with oil production occurs at a vitrinite reflectance of 0.59%, higher production rates occurs at higher thermal maturities.

In northwestern and west-central Sandoval Counties, the Mancos C has been matured into the lower oil window in the far northwestern part of the county and in adjacent parts of Rio Arriba and San Juan Counties (Figure 18, oversize version in Appendix A). This is in the area of established Mancos C oil production and the potential for oil resources in this area is high. However, as the Mancos C progressively rises out of the basin to the southeast, thermal maturity decreases and the Mancos C first passes into the upper part of the oil window. In this area of lower maturity (upper oil window), less oil has been generated so that potential is decreased with a smaller volume of oil generated per unit volume of shale. In addition, oil will be less mature, and more dense and viscous and will not move through the low-permeability sandstone layers as easily which also contributes to lower production volumes. Oil potential will be lower.

Further to the south and east, the Mancos C, as well as the overlying Mancos B and Mancos A, become thermally immature near T17N R3W and will not have generated oil. In this area, oil potential of the Upper Mancos is low.

Lower Mancos Shale

The Lower Mancos Shale is productive in the northwestern part of Sandoval County (Figure 15, oversize version in Appendix A). As previously discussed, established production is mostly from the Semilla Sandstone. The Semilla does not extend southeastward into central Sandoval County. Because production from the Semilla is commingled with production from the Mancos C, it is not possible to ascertain the economic viability of the Semilla reservoir by itself. How the Semilla would perform if penetrated by a horizontal well remains unknown.

A few wells are productive from other parts of the Lower Mancos Shale. In these wells, production from the upper Carlile shale, the Juana Lopez Member, or the portion of the lower Carlile shale below the Semilla is commingled with production from the Mancos C. There has apparently been no systematic attempt to develop resources in the non-Semilla Lower Mancos. Production from these stratigraphic units appears to be minor compared to production from the Mancos C.

Oil potential of the Lower Mancos is highest in the far northwestern part of the county where the Semilla is productive. As one moves updip to the southeast, potential becomes lower as the Semilla thins and eventually pinches out. It is unknown if other strata in the Lower Mancos can produce economically as stand-alone reservoirs or if production from these non-Semilla reservoirs will merely supplement production from the Mancos C in vertical wells. Further to the southeast near the town of San Luis in T17N R3W, Lower Mancos source rocks are thermally immature and oil and gas potential is low.

Dakota Sandstone (Upper Cretaceous)

The Dakota Sandstone is productive of oil and gas in northwestern Sandoval County (Figure 16, oversize version in Appendix A). In this area, Dakota oil potential is high. Scattered productive wells to the west of the Lindrith west oil pool suggests that reservoir quality may be uneven in this area. If so, then production may benefit through the drilling of horizontal Dakota wells in this area. To the southeast as the Dakota rises out of the San Juan Basin, there are scattered shows in exploratory wells. This indicates some potential even though associated source rocks in the Graneros Shale become thermally immature. It is possible that with the Dakota being coarser grained and with sandstone more laterally continuous than in overlying Mancos units that the Dakota is a lower impedance system than the overlying Mancos units. Therefore, oil and gas will migrate further updip than in Mancos reservoirs and source rock maturity will not exert the same control on oil and gas occurrences as in the Mancos. Therefore, an area of moderate potential may extend further to the southeast than in the overlying Mancos.

Morrison Formation (Jurassic)

The Morrison Formation contains no identifiable petroleum source rocks in either northwestern Sandoval County or west-central Sandoval County or in down dip areas of the San Juan Basin to the north or northwest. Therefore, the petroleum potential of the Morrison is considered to be low.

Entrada Sandstone (Jurassic)

The Entrada Sandstone has moderate to high oil potential in northwestern and west-central Sandoval County. The scattered small oil pools in the Entrada are formed by traps made by relict sand dunes on the top of the Entrada. The overlying Todilto limestones are the source rocks and the Todilto also acts as the vertical seal for the traps. The widespread oil shows in the Entrada encountered by exploratory wells drilled in this part of the county indicates that oil migrated through this area. Some was caught in the small “sand dune” oil pools as it moved updip (to the southeast). What was not caught in the traps migrated past them. Some may be caught in “sand dune” traps that have yet to be found. These would likely be small 1 to 4 well pools similar to those that have already been discovered.

Unlike the Mancos Shale oil reservoirs, the Entrada Sandstone is a low-impedance migratory system that allows oil to migrate through the Entrada long distances in an updip direction. Although small traps may be formed by relict sand dunes down dip (northwest) or updip (southeast) of established production, they may also be formed by low-amplitude folds or by faults that act in conjunction with stratal dip. Although the Todilto is thermally mature to the northwest, it is thermally immature in the west-central part of the county where it is shallower. Boundaries of thermal maturity of the Todilto source do not act to limit the area prospective for Entrada oil. Todilto-sourced oil would have migrated updip through the high-permeability, low-impedance Entrada reservoir. Therefore, the Todilto is prospective over a larger area than the shales in the shallower Cretaceous formations.

Chinle Formation (Triassic)

The Chinle Formation contains no identifiable petroleum source rocks in either northwestern Sandoval County or west-central Sandoval County or in down-dip areas of the San Juan Basin to the north or northwest. Therefore, the petroleum potential of the Chinle is considered to be low.

Permian strata

Permian strata contain no identifiable petroleum source rocks in either northwestern Sandoval County or west-central Sandoval County or in down-dip areas of the San Juan Basin to the north or northwest. Therefore, the petroleum potential of the Permian section is considered to be low.

Pennsylvanian strata

The Pennsylvanian section is thermally mature and within the oil window or the wet gas window throughout all of northwestern and west-central Sandoval County (Figure 21, oversize version in Appendix A). However, Pennsylvanian strata contain insufficient Total Organic Carbon (TOC) to be considered petroleum source rocks. Therefore, Pennsylvanian strata are considered to have low oil and gas potential throughout all of northwestern and west-central Sandoval County.

Southwestern Sandoval County (San Juan-Albuquerque Basin divide)

The southwestern part of Sandoval County has low oil and natural gas potential. In this area, the Lower Mancos Shale, the Dakota Sandstone and the Morrison Formation are exposed at the surface. The Upper Mancos Shale and younger strata have been removed by erosion. Limestones of the Todilto Formation, which are potential source rocks, are thermally immature (Figure 20, oversize version in Appendix A) and therefore are unlikely to have sourced oil so the Entrada will be water filled. Where the overlying Lower Mancos Shale is exposed at the surface and has not been eroded, it will also be thermally immature and nongenerative. Because deeper strata (Triassic, Permian, Pennsylvanian) are not known to contain sufficient organic matter to have generated appreciable volumes of oil or gas, these strata have a low oil and gas potential.

There are several bodies of Tertiary age intrusive rocks in southwestern Sandoval County. Cabezon Peak is the most notable of these. These are relatively small intrusive bodies. During the intrusion of the magmas that formed these igneous rock bodies, the heat emanated from the magmas may have resulted in local maturation of intruded shale source rocks. However, this effect is usually confined to a small halo around the intrusive rock body and would not result in more widespread maturation of an immature source rock. Any oil fields that would result from this local maturation will be small and confined to a small maturation aureole around the igneous body.

Albuquerque Basin

The Sandoval County part of the Albuquerque Basin has a low to moderate oil and gas potential. On the eastern and western margins of the basin where Upper Cretaceous and Jurassic strata are exposed (Figure 5, oversize version in Appendix A), petroleum source rocks (Mancos Shale, Todilto Formation) will be thermally immature. Any traps in these shallow areas along the basin flanks will likely have been breached either by exposure at the surface or through fracturing associated with the rift-bounding faults.

In the deeper, central part of the basin, thickness of the Tertiary basin fill strata exceeds 4,000 ft in south-central Sandoval County and thickens to the south to more than 5,000 ft in Bernalillo County where the basin is deeper (Figure 8, oversize version in Appendix A). Tertiary strata do not appear to contain any significant organic-rich source facies. Therefore, any oil or gas within Tertiary sandstone reservoirs would have had to migrate vertically upward along faults from the Cretaceous section. Because of the relatively low maturation of Cretaceous shales, any generated volumes of oil will have been limited and upward migration will have likely resulted in diffusion of the hydrocarbons.

As previously discussed, the Lewis Shale and the Menefee Formation (Upper Cretaceous) are thermally immature and have not generated significant volumes of oil or natural gas in the

Sandoval County part of the Albuquerque Basin. The most likely resource in these units will be biogenic gas, which typically occurs at low pressures and is a limited, low-grade resource. The Chacra sandstone facies does not appear to be present in the Albuquerque Basin. The Chacra facies is the productive part of the Lewis Shale in the San Juan Basin. Its absence in the Albuquerque Basin further limits oil and gas potential of the Lewis.

The Mancos C unit at the base of the Upper Mancos Shale has been matured to the uppermost part of the oil window in large portions of the Sandoval County part of the Albuquerque Basin. Oil resources may therefore be present in the Mancos C. However, when compared to the Mancos C in the far northwestern part of the county the resource will be limited in volume because the Mancos C in the far northwestern part of the county has been matured to peak oil generation. The underlying Lower Mancos Shale, also matured into the uppermost oil window, will also have a limited oil resource compared to the Lower Mancos in the northwestern part of the county. In low-permeability unconventional reservoirs such as the Mancos C, optimum oil production in any particular shale unit will take place where thermal maturation has proceeded into the lower part of the oil window. Peak oil generation is obtained where vitrinite reflectance is in the 0.9% to 1.0% range (Hunt, 1996; Huc, 2013; Merrill, 1991). Although oil will begin to be generated at vitrinite reflectance values of approximately 0.6% as is the case with the Mancos C in the Albuquerque Basin, larger volumes of oil will be generated as the source rock attains peak oil generation. Consequently, production will be greater in areas where the shale is more mature. Using the example from the Woodford Shale (Devonian) of Oklahoma although the lowest thermal maturity associated with oil production occurs at a vitrinite reflectance of 0.59%, higher production rates occurs at higher thermal maturities (Cardott, 2014). Therefore, yield per volume of shale will be less in most of the Sandoval County part of the Albuquerque Basin than in the far northwestern part of the county.

Within Sandoval County, the Mancos C is present at greater depths along the central axis of the Albuquerque Basin than in the shallower fault blocks to the east and to the west of the central axis. In the deepest area, Connell (2008b, his cross section A-A') indicates the Mancos C may be as much as 7500 ft deeper along the central axis than in the Shell No. 1 Santa Fe Pacific well located approximately 6 miles to the west. As previously discussed, the Mancos C has been matured into the uppermost part of the oil window in that well. At the greater depths, the Mancos C has probably been matured into the lower part of the oil window in the deeper, central part of the basin where Connell (2008b)'s cross section suggest it may occur at a depth of approximately 13,000 ft. Oil potential will therefore be higher in this area. It is also possible that the Mancos C is within the thermogenic gas window in this area with a thermal maturation similar to what is found to the south in the Bernalillo County part of the basin. If that is the case, then the lower oil window will be limited to narrow bands on the flanks of the central axis where the Mancos C dips toward the axis. Because no wells have been drilled into the deepest part of the basin in Sandoval County, there is no data to ascertain which scenario may be correct.

Any wells that are drilled into either the Upper Mancos or the Lower Mancos will maximize production if the wells are drilled horizontally rather than vertically through the pay section. Data from recent exploration wells completed in the Mancos C in the San Juan Basin indicate that first-year production from horizontal wells is, on the average, 9.4 times more than first-year production from vertical wells. In a low-permeability reservoir such as the Mancos, the reservoirs will need to be hydraulically fractured during the well completion process. Completions without hydraulic fracturing will only be effective if the well intersects a natural fracture system that is sealed in such a way as to retain oil in the fracture system.

Black (1982) reported shows of wet gas (wet gases are gases that contain substantial quantities of natural gas liquids – ethane, propane & butane – in addition to methane, which by itself constitutes dry gas) in the Dakota Sandstone in the Shell No. 1 Santa Fe Pacific well. A drill-stem test of the Dakota, as well as drill-stem tests of the Entrada Sandstone and the Yeso Formation (Permian) in this well recovered only water and drilling mud. Presumably the tests in the Entrada and the Yeso were also prompted by shows encountered while drilling the well. Given that the Lower Mancos Shale, the presumed source rock for the Dakota, is only matured to the upper part of the oil window in this well, it is possible that the wet gas was generated *in situ* by the Lower Mancos and subsequently migrated into the Dakota. Alternatively, the wet gas may have originated in source rocks in the deeper basin to the south and migrated up faults into the Dakota and thereafter migrated updip through the Dakota. In either case, it is possible that gas may be trapped in the Dakota updip of the location penetrated by the Shell No. 1 Santa Fe Pacific well. It is possible that a horizontal well test of the Dakota may have recovered gas that the drill-stem test in the vertical well could not.

Limestones in the Todilto Formation are thermally mature in the deeper areas of the Sandoval County portion of the Albuquerque Basin. Although data are sparse, it appears that thermal maturity is near the boundary of the upper part of the oil window and the lower part of the oil window. As is the case in the San Juan Basin, the underlying Entrada Sandstone is the most likely reservoir for oil sourced in the Todilto. Traps may conceivably be formed by either relict sand dunes on the upper surface of the Entrada or by fold and fault configurations associated with structure in the subsurface of the basin. The overlying Todilto limestones and anhydrites will act as the seal for the traps. With a highly permeable reservoir such as the Entrada Sandstone, wells do not need to be artificially fractured in order to produce oil. With a higher thermal maturity in the Todilto than in the shallower Cretaceous source rocks, it appears that the Todilto-Entrada couplet may have generated and trapped more oil than would be found in the shallower Cretaceous shales and sandstones.

Pre-Entrada strata have not been demonstrated to contain significant petroleum source rocks in the Sandoval County part of the Albuquerque Basin. Therefore, the petroleum potential of the pre-Entrada section is considered to be low based upon present, albeit sparse, data. Additional drilling, particularly into the deep Pennsylvanian strata, is required to obtain sufficient data necessary to thoroughly evaluate the pre-Entrada section.

SUMMARY of OIL and NATURAL GAS DRILLING and PRODUCTION TECHNOLOGIES as APPLIED to SHALES

Traditionally, oil and natural gas wells have been drilled vertically downward from the land surface until they penetrate reservoir rocks. Vertical wells have multiple sizes of casing installed in them, each with cement that is injected between the outside of the casing and the rocks surrounding the well. This type of well construction prevents fluids (oil, gas, or deep subsurface saline brines) from migrating upward between the interval between the outside of the casing and the rocks surrounding the drill hole. A more extended description of vertical well construction is given in the New Oil and Gas Technology issue of Lite Geology which is included in Appendix C of this report.

Vertical wells in shales and other ultra-low permeability rocks that bear oil or natural gas generally will not be productive of sufficient volumes of oil or gas to enable large-scale development unless the shale has been naturally fractured by natural tectonic forces. Examples of economic oil accumulations in the San Juan Basin include the Puerto Chiquito Mancos oil pools on the eastern flank of the basin in Rio Arriba County (see Greer, 1978a, 1978b). In these oil accumulations (known as "pools") a sandy brittle zone in the Mancos C shale has been naturally fractured while overlying and underlying more plastic, non-sandy shales remain unfractured. This geometric arrangement of fractured and unfractured shales results in oil, which had been generated within the shales, migrating into the naturally formed fractures where it is retained (or trapped). If the natural fracture system is sufficiently dense and extensive then the oil may be produced by vertical wells at rates that will render the wells economically viable. If the natural fracture system is less dense or less extensive, then sufficient volumes of oil production may in some cases be obtained by artificially fracturing the shale. The artificial fractures, which extend out from the wellbore, increase the surface area of the shale that the well is in contact with. In most cases, oil that has migrated into thin sand layers within the shale will then flow into the artificial fractures. Prior to 1950, artificial fracturing was accomplished by using downhole explosives in the well. When explosive fracturing was used, the portion of the well that was to be fractured was left uncased. Explosive fracturing is no longer done.

Starting in 1950, hydraulic fracturing replaced explosive fracturing as it was safer, more effective, and easier to control. With hydraulic fracturing, the entire drill hole has casing cemented in it. The casing is perforated with holes in the portion of the well that is to be fractured. A mixture of water and sand is pumped into the well at high pressure. When the pressure exceeds the strength of the rock that is behind the perforations, fractures begin to slowly develop in the rock in a process that is distinctly different from explosive fracturing. The water and sand move into the fractures, which will continue to grow and open wider, although there are mechanical limits to how large the fractures can become and in most cases the induced fractures extend only a few 10's of feet to a few hundreds of feet from the well. When the pressure is released, the water flows back and is captured at the surface but the sand stays in the artificial fractures and keeps

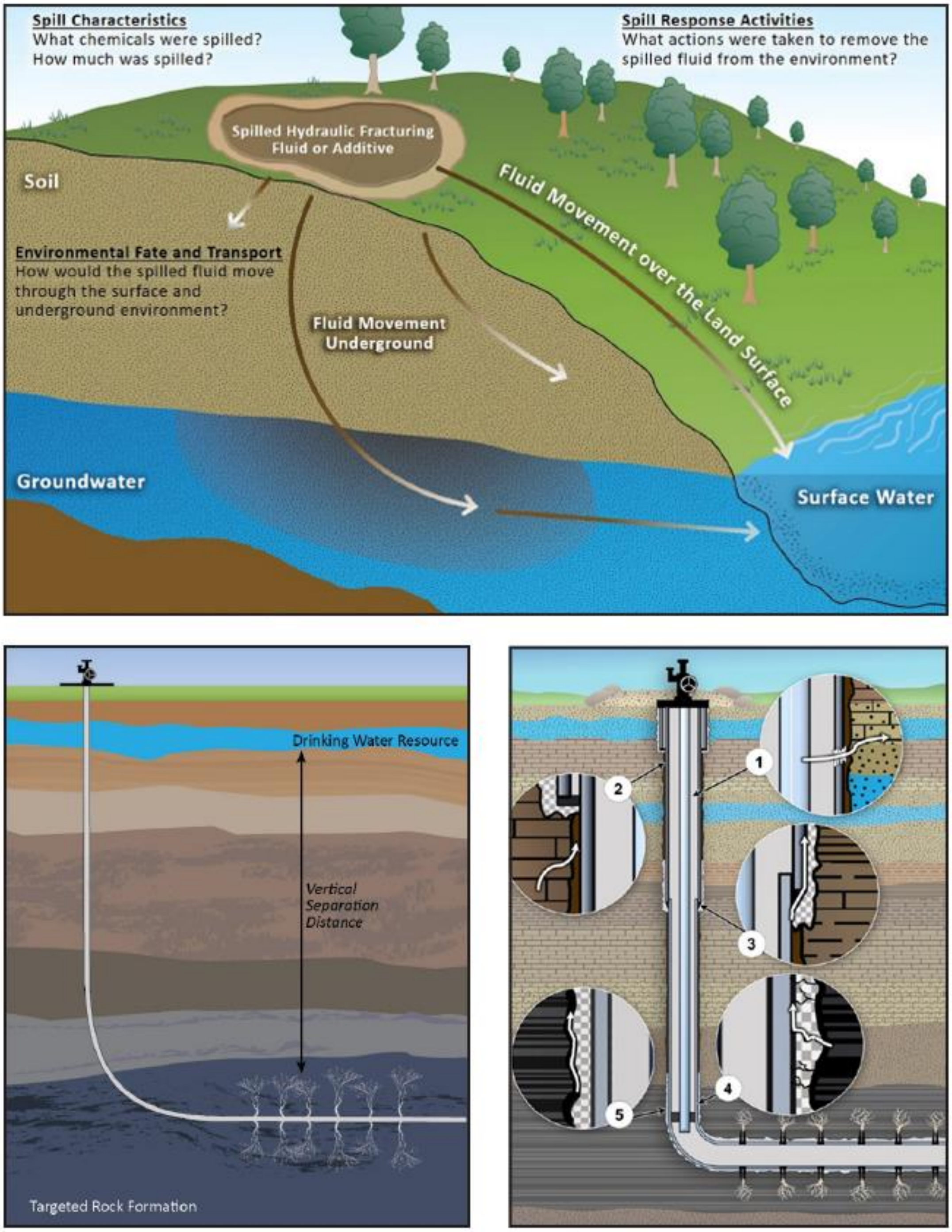


Figure 22. Conceptual model of pathways leading to hydraulic fracturing-related groundwater contamination, showing (a) contamination from surface spills, (b) possible pathway from target reservoir to aquifer, and (c) leakage from poor casing. Adapted from EPA (2016).

them open. Since 1950, more than 90% of vertical wells in New Mexico have been hydraulically fractured. Although hydraulic fracturing of conventional sandstone and limestone reservoirs in vertical wells often yields economic volumes of production, in most ultra-low permeability reservoirs such as shales adequate production volumes are not attained and the shales remain undeveloped.

In the early 2000's, techniques were developed to drill wells horizontally through shales and other unconventional, low-permeability reservoirs. Well construction and completion and hydraulic fracturing procedures in horizontal wells are summarized in the New Oil and Gas Technology issue of Lite Geology, which is included in Appendix C of this report. As discussed previously in this report, recent oil exploration and development in the Mancos Shale in the San Juan Basin has been dominated by horizontal, as opposed to vertical, wells. The target zone in the Mancos of the San Juan Basin is the Mancos C. Multiple layers of steel casing are cemented in place in the vertical part of the well and the shallower casing protects the aquifers from contamination. Steel casing is then cemented in place in the horizontal part of the well and is perforated with holes in the appropriate parts of the horizontal well segment. If the well is placed into production, the produced fluids flow to the surface through steel tubing that is placed inside the casing. To test if the concrete and steel casing leaks, the casing is pressure tested (i.e., bond tests) along their length (OCD, 2008).

Once the drill hole has been completed and cased, then the casing in the horizontal part of the well is perforated and developed (Fig. 22b; Economides and others, 2012). After being perforated, discrete lengths of the horizontal well are isolated and the well is stimulated, or hydraulically fractured, by pumping a slurry of water, some chemicals and proppant (mostly sand with some other additions) into the isolated portion of the well (Economides and others, 2012). By overpressuring the well, fractures are created or older fractures are opened (Yew and Yang, 2015). These fractures propagate a finite distance based on the amount of fluid pumped in and its pressure—this is a controlled process (Fig. 22b; Economides and others, 2012; and Yew and Yang, 2015). Recently, hydraulic fractures are generally designed to not propagate more than a few hundred feet from the well at most. If the forces used to generate the hydraulic fracture cross permeable faults, fluids can propagate up and down the fault (EPA, 2016).

All of these operations require equipment at the surface site, generally at a pad that has been constructed (Economides and others, 2012; and EPA, 2016). Drilling does require fluids that can, if spilled, contaminate groundwater and surface water (Fig. 22a; EPA, 2016). One advantage of using horizontal wells for oil and natural gas production is that far fewer wells are needed to obtain production. If a well is drilled horizontally through the reservoir for a distance of about one mile, then the horizontal well will take the place of four vertical wells which would in most cases be drilled at distances of 1320 ft from each other. If the horizontal segment of a horizontal well is drilled for a distance of two miles, then a single well replaces eight vertical wells. Increasingly in southeastern New Mexico, horizontal wells are drilled for a distance of two miles. Fewer wells results in fewer penetrations of the shallow aquifers, which minimizes the possibility of contamination of the aquifer from a well, although with proper well construction and maintenance risk of contamination of a shallow aquifer by a well is extremely low.

After the installation of the well and pumps, oil and gas are then moved to the surface. Within the formation, brine is found with oil and gas and is pumped to the surface with the oil and gas (Economides and others, 2012). This brine, or produced water, is not allowed to be put in the aquifer or in surface water in New Mexico. It is often re-injected into a different unit. However, this injection is generally done away from the pad in another well. Spills from storing and transporting the brine is another possible pathway for drinking water contamination, as is storing and transporting the oil and gas (EPA, 2016).

SUSCEPTIBILITY FACTORS FOR AQUIFER CONTAMINATION DUE TO UNCONVENTIONAL OIL AND GAS DEVELOPMENT

Unconventional oil and gas exploration and development has risks associated with it, including risks to drinking water quality (EPA, 2016), while a standard regulatory framework has yet to be developed (e.g., Rabe, 2014; and Konshnik, 2014). As Sandoval County considers its unconventional oil and gas resources, it is important to also begin assessing the possible susceptibility of groundwater resources to contamination during oil and gas operations. Water quality susceptibilities include leakage of hydrocarbons and saline brines from the target reservoir upward into aquifers via direct transport through the reservoir, through faults and fractures or through leaky boreholes (EPA, 2016). Another set of susceptibilities to water quality include leakage from spilled fluids at the surface that infiltrate into groundwater (EPA, 2016). Just like in other regions around the country, in Sandoval County groundwater contamination susceptibility from unconventional oil and gas is largely a function of good operational practices, vertical sediment and sedimentary rock thicknesses between the hydrocarbon resource and aquifers, depth from the surface to groundwater, and horizontal proximity of water wells to oil and gas boreholes (EPA, 2016). To be clear, we are not considering the risks of induced seismicity due to unconventional oil and gas operations and disposal of produced waters, only the susceptibility to groundwater contamination.

In this section, we provide a brief summary of major risk factors of aquifers due to unconventional oil and gas development. In the last decade, with the combined advent of horizontal drilling and more extensive hydraulic fracturing, a number of possible cases of groundwater contamination by oil and gas development activities have been reported (reviewed in Vidic and others, 2013; and EPA, 2016). In response to this, several groups have worked to understand factors that make regions susceptible to contamination by unconventional oil and gas development. In 2016, the US EPA published a large review of contamination risks associated with unconventional operations. This study integrated both original research, and reporting to state and federal regulators. Its results are consistent with the non-EPA peer-reviewed scientific literature—both in the environmental science and the oil-and-gas fields—and represent a general consensus-view of contamination risks from unconventional operations. Much of the following discussion is based on this report.

Risk factors include, but are not limited to leakage along existing wellbores, surface spills of oil and gas or chemicals used in well development, leakage of hydrocarbons along faults and fractures, and direct leakage from the developed formation to the aquifer (Fig. 22; EPA, 2016). Additionally, many regions undergoing development are semi-arid with limited freshwater groundwater supplies, and hydraulic fracturing requires water of variable qualities (Fig. 23; Gallegos and others, 2015). Another major risk factor includes the completion of oil and gas wells in the same geologic units as an aquifer, especially near the hydrocarbon-water boundary or near water producing wells (EPA, 2016).

Across North America, one of the shortest pathways for drinking water contamination is from spills of brine, hydrocarbons and specialized operational fluids (i.e., proppants) at the surface (EPA, 2016). This can happen during development of the resource, during pumping at the well head, and at storage facilities (Fig. 22a). This challenge, fortunately, is universal, and regulations of various stringencies have been implemented to mitigate these risks (EPA, 2016). Nonetheless, depth-to-water and the need for groundwater resources to communities and residents should be considered during planning (Lange and others, 2013). For example, operations near municipal wells that are a community's sole drinking water supply should be avoided, and oil and gas operations over shallow groundwater tables should be avoided (EPA, 2016).

For all leakage pathways, the combined pressure and buoyancy of the oil and gas reservoir must be both greater than hydrostatic pressure (i.e., overpressured), and greater than the bottom pressures of the aquifer for the hydrocarbons or brines to flow into the aquifer (Lange and others, 2013; and Kissinger and others, 2013). In other words, there must be a driving force to push hydrocarbons from the reservoir into the aquifer. For leakage, two timescales are of concern: short-term overpressuring of the reservoir during fracturing; and long-term overpressuring of the reservoir (Lange and others, 2013). Excessive short-term overpressuring during operations can lead to unintended fracturing of existing wellbore casings and previously sealed fractures and faults, and short-duration flows of fluids from reservoir rocks into the aquifer (EPA, 2016). Effects of excessive operational overpressures can be mitigated by having thick or multiple low permeability strata between the hydraulically fractured reservoir and the aquifers, and by using moderate hydraulic fracturing pressures (EPA, 2016). Additionally, before operations commence, the pressure of the reservoir needs to be measured and considered as a driver of risk to drinking water supplies.

Long-term (i.e, existing) overpressures provide a driving force for contamination of the aquifer by brines and hydrocarbons if there is a fast pathway from the reservoir to the aquifer (Lange and others, 2013; and EPA, 2016). These overpressures are caused naturally in low permeability rocks, such as shales, by compaction, and oil and gas generation (Economides and others, 2012). However, if a seal is compromised during operations, whether that is a leaky wellbore (Brownlow and others, 2016) or reactivation of fractures and faults (Lange and others, 2013; and EPA, 2016), then natural overpressures can cause brines and hydrocarbons to move upward (Lange and others, 2013). To avoid this, reservoirs should be separated from aquifers by thick or multiple seals, operationally caused damage should be limited, and stimulation near existing wellbores should be limited (EPA, 2016). As before, the reservoir pressures should be assessed before drilling, not only for operational requirements but also to assess likelihood of leakage pathways.

To understand the risks of fracturing, a series of studies (Fisher and Warpinski, 2011; Davies and others, 2012; and Flewelling and others, 2013) have been performed to answer the question: how far do hydraulic fractures go? Across the country, and in regions that are geological similar to New Mexico, hydraulic fractures are extremely unlikely (<1% exceedance probability) to propagate more than 1,300 ft, with the vast majority of hydraulic fractures propagating 100s of feet at most (Davies and others, 2012). This estimate is also valid for short-term fluid propagation in faulted terrains (Flewelling and others, 2013). Once again, if the system is overpressured (Lange and others, 2013; and Kissinger and others, 2013), longer-term leakage may be possible.

Faults and fractures are often considered to be significant risk factors for aquifer contamination during oilfield operations. They can provide high permeability pathways for fluid to flow from high pressures to low pressures (Williams and others, 2015; Manzocchi and others, 2010; and Lange, 2013). However, faults and fractures can have low permeability (Rawling and others, 2001). This can happen when the damaged region of the fault or fracture is filled with a low permeability material. Loss of permeability is usually caused by either preferential cementation of a damage zone due to brine movement up the fault, or due to smearing or formation during failure of clay minerals in the damage zone (Williams and others, 2015). It is difficult to assess these risks without drilling or extremely detailed geophysical surveys, as the flow pathways can be affected by underlying fluid chemistry and timing of fault slip (Williams and others, 2015). However, leaky faults and fractures are much less likely in clay-rich rocks, such as shales (Williams and others, 2015; Lange and others, 2013) and leakage makes oil and gas development difficult to the point of being uneconomical (Manzocchi and others, 2010).

The combination of hydraulic fracturing and horizontal drilling has led to new wells being drilled in existing, older fields that have both actively pumping wells and abandoned wells. Wells with a 'leaky' casing that penetrate through or near the proposed reservoir can provide a fast path for reservoir fluids to migrate upwards into aquifers (Fig. 22c; EPA, 2016; and Brownlow and others, 2016). Ultimately, the mitigating factors for risk associated with this leakage are ensuring new wells are carefully completed, lack of overpressures in the reservoir, and having a significant distance between the aquifer and reservoir.

Unrelated to contamination concerns, hydraulic fracturing operations require water, which is the main fluid that is used to induce fractures. This water, oftentimes, has been freshwater from aquifers, though both the volumes and quality of water used have been decreasing in the recent years (Gallegos and others, 2015; Kondash and Vengosh, 2015; and EPA, 2016). Nonetheless, the volume of freshwater required for unconventional oil and gas operations should be assessed in the context of available freshwater supplies (EPA, 2016). The risk to water supply volumes can be mitigated by using brackish water resources, decreasing the required volume of water needed for each well, and by reusing produced or primary 'frac' waters for additional hydraulic fracturing.

In short, several factors are key to lowering the risk of contaminating aquifers during unconventional oil field operations (i.e., horizontal drilling and hydraulic fracturing):

- Having multiple and thick (1300 ft above target reservoir) geologic seals between the target reservoir and the aquifers (see Fig. 23 for Albuquerque Basin).
- Management of surface operations, and avoidance or regulation of drilling in regions with shallow water tables or critical aquifers.
- Ensuring new oil wells have good casing cement integrity and consideration of the completion depths of active or abandoned oil wells.
- Assessment of reservoir pressures; strongly overpressured reservoirs are more likely to leak upward into aquifers.
- Assessment of fracture and fault permeability from depth into the aquifer.

Additionally, hydraulic fracturing requires significant volumes of water; once again, industry has been decreasing both the required volumes and the required water quality. These required resources should be balanced against the available freshwater resources.

Pre-Oil and Gas-Development Recommendations

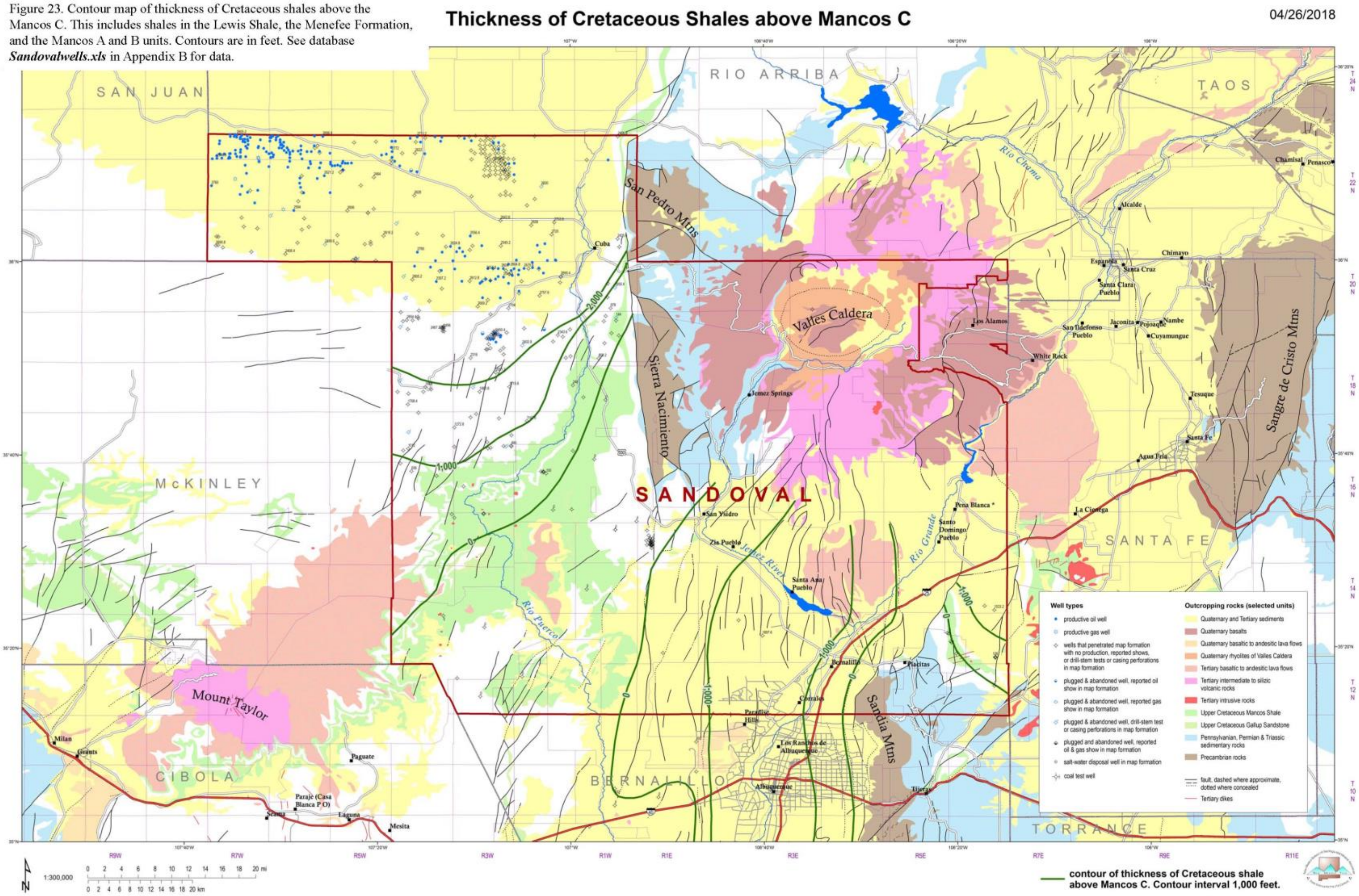
Before unconventional oil and gas activities proceed, pre-development monitoring and water chemistry sampling are the key to being able to clearly and unequivocally document changes post-development. These measurements are relatively broad, but generally include specialized water chemistry and dissolved gas measurements not commonly performed in water quality monitoring (Jackson and others, 2013b). This is because the major concerns for drinking water and for general water analysis often are not able to indicate what the source of fluid or constituents are—they only indicate the general chemistry of salts and common organic contaminants. However, even when more specialized sampling is undertaken and a change is observed, it often has required additional effort to attribute the change to a specific cause, whether from oil and gas operations or from natural causes. However, without high quality data on water chemistry before operations, changes are anecdotal and cannot be definitively evaluated (Jackson and others, 2013b; and EPA, 2016).

Several studies have been undertaken to understand the source of methane, salts and water in groundwater within actively developed oil and gas regions. These fall into several, relatively broad categories, most of which are summarized in Jackson and others (2013b):

1. Analysis of changes in major ion chemistry (Warner and others, 2012; and Vider, 2013).
2. Ongoing sampling of organic carbon including hydrocarbon phases, carbon isotopes and dissolved gases in groundwater (Jackson and others, 2013a; and Nicot et al, 2017).
3. Stable water isotopic concentrations and radiogenic isotope ratio changes indicative of deeper waters that are dissimilar to modern, local water (Darrah and others, 2014, Nicot and others, 2017).
4. Changes in groundwater ages and stable carbon isotopes (Jackson and others, 2013a; and Nicot and others, 2017).
5. Changes in dissolved sulfur isotopic signatures (Darrah and others, 2014).
6. Changes in noble gas concentrations (Darrah and others, 2014).
7. Analysis of hydrocarbon reservoir pressures (Lange, 2013; and Kissinger, 2013).

Not all of these measurements are required, but the best suite of measurements should be identified for each study region. With that said, some of the analyses, such as the general chemistry, total dissolved gases, and isotopic sampling, are suited for broad sampling, while others like noble gas concentrations, groundwater ages and changes in organic carbon phases, because of cost, difficulty of sampling and specific requirements at the well head, may need to be more focused. Additionally, specific, high impact wells (high capacity or single-source municipal wells, wells that are completed at depths near hydrocarbon source rock, or wells located near or in proposed oil fields) should be identified for close monitoring. It is also necessary, in all locations, to assess the pressure of the oil and gas reservoir relative to hydrostatic pressures: overpressured systems can leak more easily and for longer durations than normally- or under-pressured systems.

Figure 23. Contour map of thickness of Cretaceous shales above the Mancos C. This includes shales in the Lewis Shale, the Menefee Formation, and the Mancos A and B units. Contours are in feet. See database ***Sandovalwells.xls*** in Appendix B for data.



DISTRIBUTION OF AQUIFERS AND THEIR SUSCEPTIBILITY TO CONTAMINATION

In this portion of the assessment, we present a reconnaissance level hydrogeologic assessment of unconventional oil and gas operations hazards to drinking water across Sandoval County. We differentiate between a location's susceptibility to contamination, which is how difficult it is to contaminate an aquifer via different pathways, and the risk of contamination, which roughly account for the impacts of contamination. In this study, because of its broad area and limited scope, we present this in an informal, qualitative sense.

This effort has been built on a literature review and data compilation of the hydrogeology of Sandoval County, building largely on the work of Stone and others, (1983), Hawley and Haase (1993), Johnson and Campbell (2002), Plummer and others (2004), Connell (2006), Connell (2008), Bartolino and others (2010), Grauch and Connell (2013), and Kelley and others (2014). Sandoval County crosses multiple geologic and physiographic boundaries that have largely evolved since the Cretaceous—the latest time when the oil and gas source rocks were deposited—implying that there are many aquifer units across the region and that the structural geology (faults and fractures) is complex. This makes even a reconnaissance level assessment challenging. For the purposes of the hydrogeologic assessment, we have split Sandoval County into six regions: the Colorado Plateau region, the Nacimiento-Laramide Uplift region, the Rio Puerco Fault Zone region, the Albuquerque Basin region, and the Placitas-Sandia Mountain-Hagan Embayment region. For each of these regions, we summarize the geology of primary aquifers, depth-to-water and well completion depths, overall water quality of each aquifer, and the likely susceptibility to contamination from unconventional oil and gas operations. The difference between the depth-to-water and well completion depth defines the aquifer interval, with the well completion depths roughly corresponding to the depth of the actively developed aquifer. This is distinct from the bottom of the aquifer unit, which is generally poorly constrained but is defined as either the depth that water becomes unsuitable to drink or as the base of the productive aquifer's geologic unit.

Of special concern is the Albuquerque Basin, where there has been limited previous oil and gas exploration and where there is a large metropolitan area reliant on groundwater for their drinking water supply; much of the rest of Sandoval County is sparsely populated. In the Albuquerque basin, we integrate the depth to the top of the oil and gas seals, the different hydrochemical zones, and provide more detail on the water well completion formations and water levels.

<u>Sandia Mountains, Placitas and Hagan Embayment (SMPHE)</u>

This region stretches from the northern Sandia Mountains northeast across the Placitas region toward the Galisteo River (Fig. 24, oversize version in Appendix A). The area has high precipitation in the mountains and semi-arid conditions in the lower elevations (Bartolino and others, 2010). Outside of the Placitas area and in the area around Sandia Park just north of the Sandoval county line, the region is not well populated, but does contain small communities and rangeland operations (Fig. 24, oversize version in Appendix A; Bartolino and others, 2010). Some streams are perennial in the Sandia Mountains and for short reaches downstream of springs around the base of the Sandia Mountains (Johnson and Campbell, 2002), but most streams are ephemeral, flowing either during snow-melt or during monsoon rains (Johnson and Campbell, 2002; and Bartolino and others, 2010).

The region consists of three sub-regions: the Sandia Mountains, the Placitas area and the Hagan Embayment. All three are on the edge of the Albuquerque basin of the Rio Grande rift, an extensional tectonic setting, and consist of a series of erosional exposures of bedrock down-dropped along faults into a basin. In no part of the area is basin-fill thick. Rather, alluvial deposits of mostly thin, poorly sorted sands and gravels shallowly overtop bedrock and fill small stream valleys, and then thicken into the Hagan Embayment. The Sandia Mountains consist largely of fractured Pennsylvanian-aged Madera Group limestones and limey sands laying on top of a thin bed of Sandia Formation conglomerates and Precambrian igneous and metamorphic intrusive rocks. Other formations present are Paleogene sedimentary rocks, a series of Cretaceous shales and sandstones, the Agua Zarca Sandstone of the lower Chinle Formation and the upper part of the Chinle Formation, the Glorieta Sandstone and San Andres Limestone, the Yeso Formation, the Abo Formation and the Bursum Formation (Fig. 24 in Appendix A; Johnson and Campbell, 2002; Cather and others, 2002; Connell, 2008b; and Bartolino and others, 2010).

Description of aquifers

The following summarizes the comprehensive study of Johnson and Campbell (2002) in the region immediately around Placitas and builds on the regional study of Plummer and others (2004), the study of Bartolino and others (2011) of the east flank of the Sandia Mountains, and geologic maps of Cather and others (2002) and Connell (2008b). This region overall is characterized by thin alluvial aquifers underlain by fractured aquifers in Paleozoic to Mesozoic rocks in the Placitas region (Johnson and Campbell, 2002), secondary fractured aquifers in Precambrian to Paleozoic rocks, and limited use of Tertiary sedimentary aquifers in the Hagan Embayment (Bartolino and others, 2011). The region's aquifers are recharged both by mountain block recharge from the Sandia Mountains and by focused mountain front recharge in several large, mostly ephemeral, streams (Johnson and Campbell, 2002; and Bartolino and others, 2011). While minor aquifers that are adequate for small domestic or stock tank wells are present in all of the rocks in the region, the primary aquifers are in alluvium deposited along alluvial fans of the rocks in the region, the primary aquifers are in alluvium deposited along alluvial fans and streams spilling off of the Sandia Mountains (Johnson and Campbell, 2002; and Bartolino and others, 2011), shallow Santa Fe Group deposited by the ancestral Rio Grande and old alluvial fans both from the Sandia Mountains and from the Ortiz Mountains (Bartolino and others, 2011), and in the Pennsylvanian-aged Madera Group limestone members that cap the Sandia Mountains and plunge into the basins (Johnson and Campbell, 2002; Connell, 2008b; and Bartolino and others, 2011). Springs are present in the Permian-aged Abo Formation, which is composed of siltstones and fine sandstones with preserved paleochannels possibly acting as conduits (Johnson and Campbell, 2002). However, the paleochannel sandstones are rare in the region. Fractured Precambrian igneous rocks also serve as minor aquifers, as do fractured and sandy intervals of Cretaceous rocks, which are primarily shales with interbedded layers of fine sands (Johnson and Campbell, 2002; and Bartolino and others, 2011).

The alluvial sediments were deposited on top of bedrock or fill valleys eroded into bedrock. Thicknesses vary from 10s of feet to a few hundreds of feet (Connell, 2008b), often with relatively shallow groundwater tables (Fig. 25; Johnson and Campbell, 2002; and Bartolino and others, 2010). The grain size and mineralogy of these deposits are a function of the type of and distance from the source terrain. In this region, most alluvium is sandy but contains significant silt and clay-sized fractions. However, the reported transmissivities and hydraulic conductivities are relatively high, allowing rapid infiltration of water and other liquids. In areas where the alluvial sediments overlie low permeability rocks, it is possible and likely that perched aquifers exist. Where alluvial sediments overly higher permeability rocks or basin-fill (older unconsolidated sediment), alluvial aquifers are generally well connected with the lower strata. In this region, alluvial aquifers generally receive recharge either from infiltration along streams or from upward flow from permeable units like the Madera Group (Johnson and Campbell, 2002; and Bartolino and others, 2011).

Additionally, thin Santa Fe Group sediments fill the Hagan Embayment northeast of the Sandia Mountains, derived primarily from piedmont sediments from the Ortiz Mountains (Cather and others, 2002; and Bartolino and others, 2010). These sediments are the Tertiary interbedded sandstone/mudstone of the Diamond Trail (450 ft thick), the muddy Galisteo (< 3200 ft thick) and coarse volcaniclastic Espinaso (1400 ft thick) Formations (Cather and others, 2002; Bartolino and others, 2010). These units, however are generally not used for water other than for stock tanks (Bartolino and others, 2010). The limited water quality data available indicates that the water is high in dissolved sulfate and total dissolved solids (Bartolino and others, 2010). The Tertiary formations commonly unconformably abut older rocks.

The Madera Group consists of a thick (49 ft to 300 ft; average of 190 ft) stack of Pennsylvanian limestones and sandy-limestones that forms a fractured aquifer (Johnson and Campbell, 2002; and Bartolino and others, 2010).While these rocks generally do not have significant primary porosity, they are densely fractured and locally dissolved throughout the region (Bartolino and others, 2010). They also lay on top of a thin conglomerate, the Sandia Formation, and the Precambrian igneous and metamorphic rocks. Because it is continuous from the peak of the Sandias, forming the prominent cliff at the top of the mountains, to the edge of the valleys in the Placitas and in the Hagan Embayment, the Madera Group is recharged from snowmelt and discharges this water into the different basins (Johnson and Campbell, 2002; and Bartolino and others, 2010). Like most fractured and karstic aquifers, it is difficult to identify clear flowpaths in the Madera Group aquifer, but water is transmitted seasonally during snowmelt and monsoonal rains (Johnson and Campbell, 2002). Where capped by the low permeability Abo Formation and younger mudstones, it forms a confined aquifer. Where open to the atmosphere, it forms an unconfined aquifer (Johnson and Campbell, 2002; and Bartolino and others, 2010). While it is permeable, the fracture porosity restricts the storage of water to a small fraction of the volume of the rock (Johnson and Campbell, 2002).

Throughout much of the SMPHE region of Sandoval County, well coverage is sparse (Fig. 25, oversize version in Appendix A). The two exceptions are around the town of Placitas and between the Ortiz Mountains and the Sandia Mountains along US-14 along the Sandoval county line (Fig. 25, oversize version in Appendix A). In these regions, wells are completed in alluvium, the Madera Group, or in various other, generally fractured formations such as the sandstone near the base of the Triassic Chinle Formation, the Jurassic Morrison Formation, or in igneous and metamorphic rocks (Johnson and Campbell, 2002; and Bartolino and others, 2010). Around Placitas, wells completed in alluvium are less than 100 ft deep, wells completed in Madera Group limestones range from less than 100 ft deep to 400 ft deep (Fig. 25, oversize version in Appendix A). Wells completed away from these aquifer units or along ridgelines are deeper, either because the depth-to-water is greater, or because the unit is less permeable and requires a longer screened interval to be productive (Johnson and Campbell, 2002; and Bartolino and others, 2010).

The majority of water levels are relatively shallow (<150 ft bgs), especially in alluvial fill and in the fractured Madera Group aquifers (Fig. 26, oversize version in Appendix A). Areas in other, more locally fractured bedrock aquifers, whether sedimentary or igneous, have deeper water tables, up to 600 ft bgs (Fig. 26, oversize version in Appendix A). In general, water tables across the region are declining (Bartolino and others, 2010), though some wells that are on preferential pathways in the Madera Group aquifer or are near channels that flow frequently in the alluvial aquifers have 'flashy' or episodically recharging hydrographs (Bartolino and others, 2010). Water table elevations in alluvial valleys or in the unconfined portions of the Madera Group roughly follow topographic trends. However, the other aquifers are more compartmentalized and do not show clear local gradients, though Bartolino and others (2010) suggested regional, topographically driven flow directions.

Figure 24. Map of generalized geology of Sandoval County, based on NMBGMR (2003).

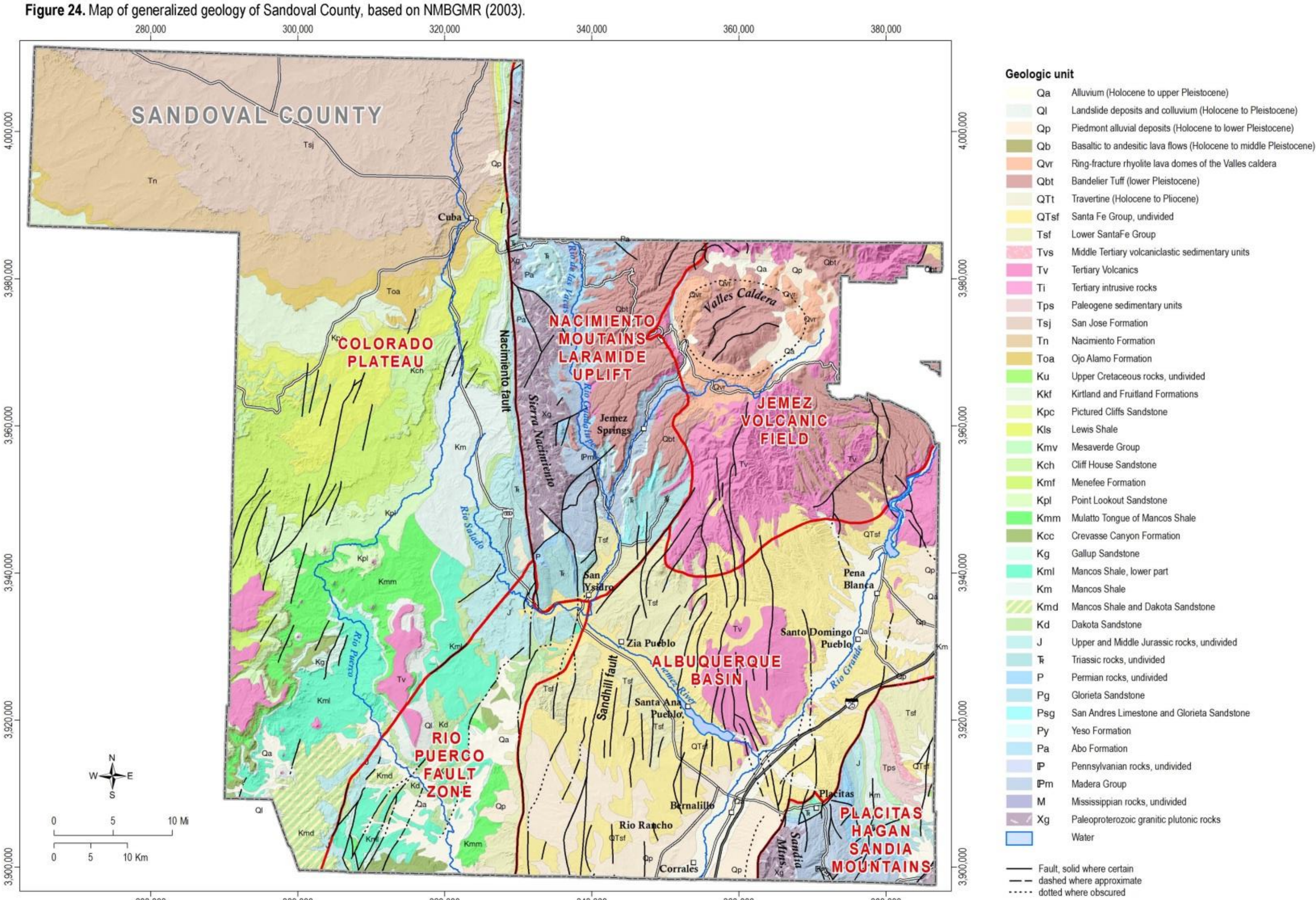
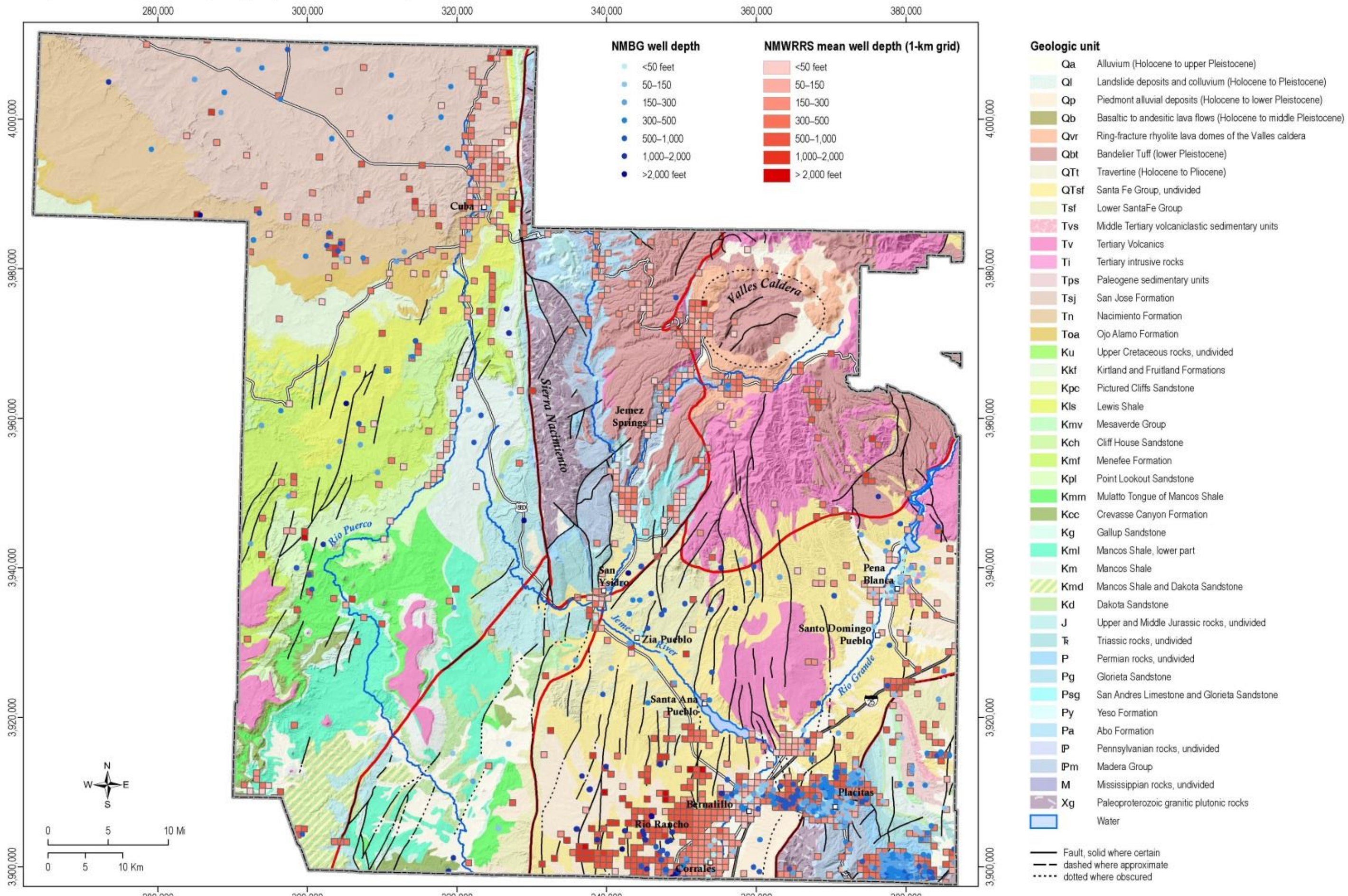


Figure 25. Map of mean well depth of New Mexico Office of the State Engineering Water Rights Reporting System (NMWRRS)-permitted wells at 1-km grid, and well depth of wells in New Mexico Bureau of Geology Aquifer Mapping Program database, overlain on geology simplified from NMBGMR (2003).

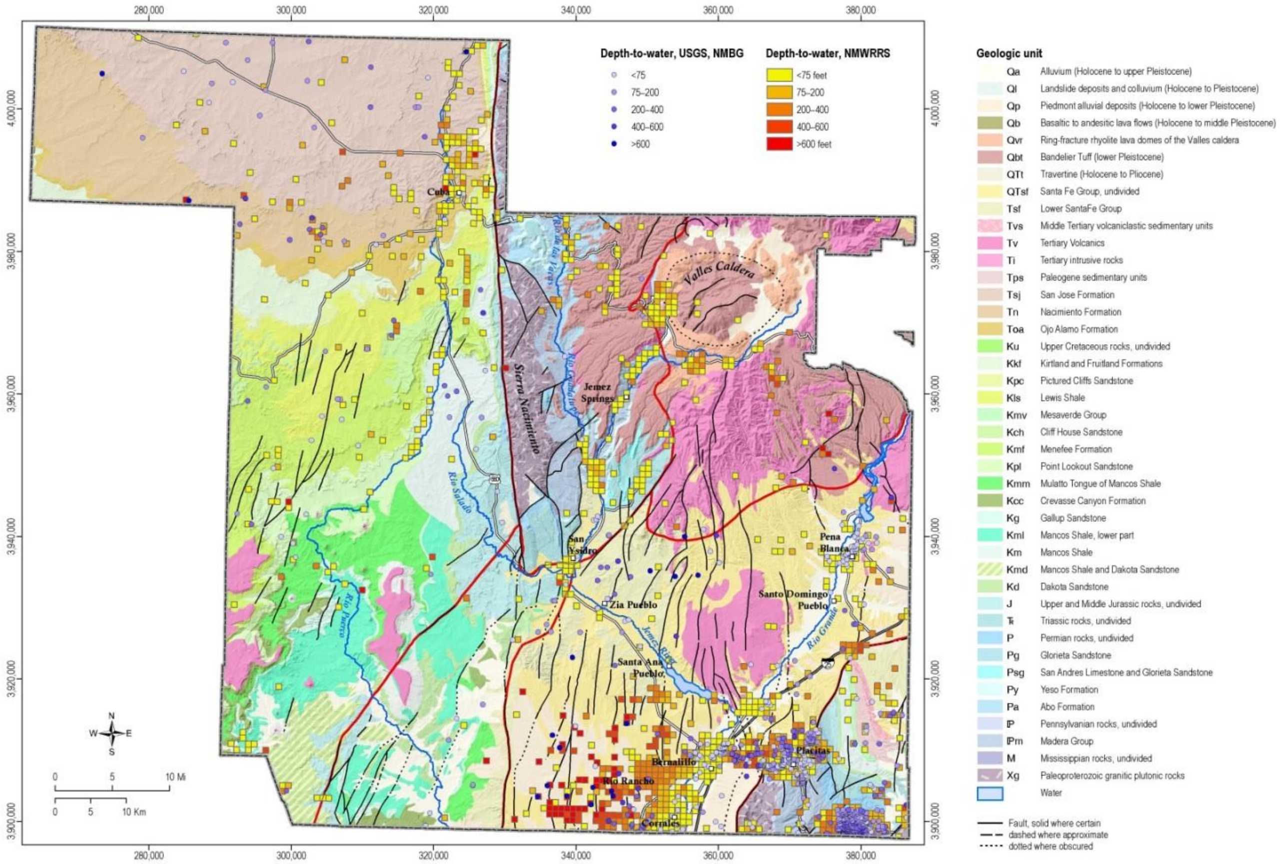


Johnson and Campbell (2002) provides a dense sampling of water quality, including general water chemistry, trace elements and stable isotope analysis, around Placitas (Fig. 26, oversize version in Appendix A), while Bartolino and others (2010) covers the rest of the region. In general, water quality in the alluvial aquifers and Madera Group aquifers is good and consists of modern waters (Johnson and Campbell, 2002; and Bartolino and others, 2010). However, where either the alluvial aquifers or the Madera Group aquifers are contacting more gypsum-rich rocks, sulfate levels and total dissolved solids can spike (Johnson and Campbell, 2002; and Bartolino and others, 2010). Many of the secondary aquifers in the region have high sulfate or high total dissolved solids, often making them appropriate only for livestock watering.

Summary and Implications for Oil and Gas Development

This region has low oil and gas potential, even for unconventional development, as discussed in the first part of this report. However, if there was development, much of the region would have low susceptibility to contamination from oil and gas development operations simply because the population density, and the water well density, is low. As usual, streams, domestic wells and municipal wells are necessarily more sensitive when considering development: accidents could have severe consequences in these areas. Development around Placitas and the string of small, often unincorporated communities along the eastside of the Sandia Mountains would similarly have a high risk of contamination because of relatively shallow water levels, fractured aquifers, direct communication with older sedimentary rocks that might be the target, and denser well networks. If oil and gas development begins in the region, there is existing water quality data to provide a base-line across much of the region, though renewed monitoring would be recommended.

Figure 26. Map of static gridded depth-to-water (ft bgs) from NMWRRS (colored by median, hashed by minimum), and most recent depth-to-water (ft bgs; well locations colored by depth-to-water) as measured by USGS, Bernalillo County Water Authority and New Mexico Bureau of Geology and Mineral Resources.



Jemez Mountains Volcanic Field

In the Jemez Mountains and stretching onto the uppermost Pajarito Plateau (Fig. 24 in Appendix A), this region consists of the Valles Caldera and associated plateaus to the east that have been subject to geothermal and volcanic activity. We have chosen not to include the western Jemez Mountains, which are largely underlain by Paleozoic rocks that were warped upward during the Laramide orogeny (uplifting of the Rocky Mountains and downwarping of the San Juan Basin; Cather, 2003), because, while partially covered with volcanic rocks flowing out of the Jemez Volcanic Field, the western portion of the Jemez Mountains lacks both geothermal systems and volcanic vents (Trainer and others, 2000). As we define it, the Jemez Mountains volcanic field in Sandoval County stretches from the northern and eastern boundary of Sandoval County to the western edge of the Valles Caldera and along the southern boundary of volcanic rocks spilling over into the Albuquerque Basin (Fig. 24, oversize version in Appendix A).

The Jemez Volcanic Field is sparsely populated and is covered largely by a combination of tribal, national forest service, and national park service land. It has several perennial streams, including the Jemez River and San Antonio Creek. Most of the other streams are ephemeral. The region ranges from 5,600 ft amsl to 11,254 ft amsl in elevation, and ranges between semi-arid to sub-humid in precipitation levels, including significant amounts of snow at higher elevations. It transitions from pinyon and juniper savannah to ponderosa pine to mixed conifer forests with increasing elevation.

Despite its relatively sparse population, several regional hydrogeology studies have been conducted or compiled. Most recently, Trainer and others (2000) summarized the previous 30 years of research on the hydrogeology and geothermal systems of the Jemez Volcanic Field; much of the following discussion is summarized from his report. Essentially, the higher elevation caldera complex drives recharge along faults, through deep circulation and via surface water-groundwater exchanges in river valleys downward and outward through the volcanic field into the lower Nacimiento-Laramide Uplift Region and possibly into the northern Albuquerque Basin (Trainer and others, 2000).

Description of aquifers

The primary aquifers in this region are alluvial, basin-fill sedimentary, and volcanic tuff and basalt aquifers (Trainer and others, 2000). In Sandoval County, these aquifers support pueblos, small communities, domestic supplies, and irrigation and livestock supply wells. Numerous springs are present along the valley cut by the perennial rivers, especially the Jemez River (Trainer and others, 2000). These springs appear to coincide with faults or the edges of the caldera where deep, old meteoric water upwells or where slightly younger but still old meteoric water flows laterally along faults. There are also a large number of snow-melt driven springs (Trainer and others, 2000). A handful of geothermal springs exist along the western edge of the

Valles Caldera. Underlying the volcanic field are uplifted and partially eroded Triassic and Paleozoic rocks (Goff and others, 2011). These form minor aquifers, at best, that feed small domestic and livestock supply wells (Trainer and others, 2000). All of the Cretaceous-aged rocks are thought to have been eroded during the Laramide orogeny and are largely not present under the western part of the volcanic field; these are the common oil and gas source rocks in the San Juan Basin (Goff and others, 2011).

Alluvial aquifers outside of the Valles caldera are generally tens to at most a hundred feet thick, have mixed sorting and permeability, and are recharged mostly by meteoric water and streamflow (Trainer and others, 2000). In the Valles Caldera, it is unknown how thick the lacustrine and alluvial fan sediments are filling Valle Grande and the other caldera rim valleys: they range from 450 ft thick to greater than 1,450 ft thick (Trainer and others, 2000; and Goff and others, 2011). These valleys contain a thick clay layer that confines the lower aquifer (Trainer and others, 2000). In the Valle Grande and in the narrow, deep slot canyons draining the east and southeastern flanks of the Jemez Mountains, the alluvial and basin-fill aquifers generally do not abut older sedimentary rocks, but back-fill against volcanic rocks (Goff and others, 2011).

The volcanic rocks within the caldera, the outflow volcanic rocks (i.e., the Bandelier Tuff), and minor eruptions cross-cutting the primary caldera flows also form a complex set of aquifers (Trainer and others, 2000). This aquifer system can be conceptualized into three systems: a shallow, and in places, perched unconfined aquifer in mostly fractured rocks; a fractured aquifer with recharge seeping through the exposed mountains into the deeper systems; and a deep geothermal system sealed partially by geothermally altered rocks that flows out of the system in unknown ways to the east and south, and along the Jemez River valley (Canon de San Diego) to the southwest (Trainer and others, 2000; and Kelley and others, 2007). Where the deep system has flowed upward to the surface, there are commonly travertine mounds, such as Soda Dam; where it is sealed, the water is hot (Trainer and others, 2000; and Kelley and others, 2007). The primary drinking water in these three systems are the high quality shallow, in places perched aquifers and recharging mountain alluvial aquifers (Trainer and others, 2000). The deeper system has poor water quality (Trainer and others, 2000). The deep aquifer system disconformably lies on top of Paleozoic and Triassic rocks (Goff and others, 2011). Little is known about the fluids in these rocks, but, because of the temperatures at depth, it is unlikely that oil and gas, or high-quality water is present.

Wells are mostly domestic supplies or livestock wells and are generally clustered along valley bottoms and lower valley flanks (Figs. 25, 26, oversize versions in Appendix A). Water levels are shallow (<250 ft bgs, with shallowest water tables at 25 ft bgs) in high elevation river valleys (Fig. 26). At lower elevations, water levels become deeper, often as deep as 500 ft bgs (Fig. 25). Little high quality, repeat data from NMBGMR or USGS has been regularly compiled in this region that is available for public use (Fig. 25), so it is difficult to evaluate if water levels are stable or not.

Summary and Implications for Oil and Gas Development

Given the lack of oil and gas potential of the region with no known reservoirs, the overall risk to aquifers is low. Similarly, the low population density lowers the susceptibility of the region to unconventional oil and gas development-related contamination, even if development began. As usual, streams and domestic wells should be considered when siting oil and gas wells, with significant stand-off distances needed to avoid surface or near-surface contamination. This is especially the case given the small geometry (narrow river valleys) and shallow water tables of the alluvial and volcanic aquifers. If development was undertaken, there appears to be a regional seal that confines the geothermal system above the possible targets that would preclude diffuse upward contamination. However, the regional fault systems appears to form preferential flow conduits, implying that development would need to be located away from them to lower contamination susceptibility.

Sierra Nacimiento-Laramide Uplift Region (SNLU)

The Sierra Nacimiento-Laramide Uplift (SNLU) region in Sandoval County forms the transition from the eastern San Juan Basin to the Jemez Mountains Volcanic Field, going from the Sierra Nacimiento and the San Pedro Mountains in the west (using the Nacimiento Fault as a boundary) to the ring-fractures of the Valles Caldera in the Jemez Mountains Volcanic Field to the east, and from the northern edge of Sandoval County to the town of San Ysidro and the southeastern edge of the Jemez River valley (Canon de San Diego) in the south (Fig. 24, oversize version in Appendix A). The Jemez River, draining out of the Jemez Mountains, is a perennial stream in this region, while the Rio Salado, which drains the eastern flank of the Sierra Nacimiento, is ephemeral (Fig. 24). Small perennial streams are present in the uplands of the Sierra Nacimiento, but become ephemeral as they drain out into the San Juan Basin. The region contains several small communities, Jemez Pueblo, and some Zia Pueblo lands; much of the region is National Forest land. Away from the main small communities, much of the region is rangeland with scattered or no dwellings.

Because of the sparse population, relatively few hydrogeologic studies have been conducted outside of Canon de San Diego and the regions directly hydrologically linked to the Jemez Volcanic Field. This includes most of the Rio Salado, the western volcanic capped-Jemez Mountains and the Sierra Nacimiento. Within Canon de San Diego, we relied on Trainer (2000) to understand the relative connectivity of the upgradient caldera complex with the canyon groundwater. Away from Canon de San Diego, the primary geologic and hydrogeologic studies we are relying on are have been Anderholm (1979), Stone and others (1983), Woodward (1987), Craigg (1992), Craigg (2000), and Kelley and others (2014).

Description of aquifers

Essentially, the region contains three types of aquifers: alluvial aquifers, perched volcanic aquifers, and Paleozoic fractured aquifers (Anderholm, 1979; Stone and others, 1983; and Trainer and others, 2000). Alluvial aquifers tend to be relatively thin with shallow water tables. In places, they may be perched, with an unsaturated zone between them and a deeper aquifer but this interpretation is difficult to verify. Aquifers hosted in the volcanic rocks of the region, primarily the Bandelier Tuff that flowed out of the Valles Caldera, have been shown to be perched, existing in locally fractured zones that do not transmit easily outward to the regional aquifers (Trainer and others, 2000). The Paleozoic strata include the Permian San Andres Limestone and Glorieta Sandstone, Yeso Formation, and Abo Formation, overlying the Pennsylvanian Madera Group and Sandia Formation (Fig. 24). All of these formations can be moderately productive aquifers. Where they are not fractured, these formations have relatively little primary porosity but can still supply low-yield domestic and livestock supply wells (Trainer and others, 2000).

Wells completed in alluvium generally have shallow (<200 ft bgs; Fig. 25) total depths and very shallow (< 50 ft bgs) depth-to-water levels (Fig. 26). Wells completed in the volcanic rocks of the region have a range of depths (< 50 ft bgs to > 300 ft bgs), and have a similar range of depth-to-water values; this shows that the volcanic aquifer is compartmented and likely perched (Figs. 25, 26). Few wells are completed in the Precambrian rocks (Fig. 25).

Many of the wells are completed in the Madera Group (Figs. 25, 26 of Appendix A). These wells have highly variable well depths (Fig. 25), likely corresponding to the degree of fracturing. Most of these wells have shallow water table (< 100 ft bgs; Fig. 26), probably due to being confined aquifers or being close to the recharge zone. Some wells, however, penetrated several hundred feet before the water table was found. Groundwater in both alluvium and in the Paleozoic rocks generally flow down the valley. However, large carbonic spring deposits and active springs are found in Canon de San Diego. Trainer and others (2000) and Kelley and others (2007) indicate that these are likely caused by geothermal water flowing out from the volcanic complex through a deep aquifer system, that intersects a permeable fault with upwelling to the surface along that fault.

Trainer and others (2000) compiled groundwater chemistry results from throughout the region. In Canon de San Diego, the water is relatively fresh though the TDS (total dissolved solids) can increase (that is, the water becomes saltier) when geothermal water mixes with it at tributaries and faults. The Rio Salado, however, has generally poorer water quality with higher total dissolved solids and more sulfate (see Craigg, 1992).

Within the study area, little groundwater sampling has occurred focused on freshwater, rather than geothermal water resources, or on wells rather than springs. Trainer and others (2000) do successfully classify the water into different aquifer systems, but were limited by the lack of well and spring density.

Summary and Implications for Oil and Gas Development

Given the lack of oil and gas potential of the region, the overall risk to aquifers is low. The majority of aquifers in this region is either in alluvium or in the Madera Group fractured limestone aquifer. Water quality is controlled by (a) faults acting as conduits from deeper geothermal waters, (b) recharge from streams, and (c) dissolution of salts from nearby sedimentary rocks. In this case, it is because of the lack of thickness of sedimentary rocks and the sedimentary section contains no identifiable petroleum source rocks. The region is susceptible to surface contamination, because of the high permeability of the alluvial and, in places, fractured volcanic and Paleozoic sedimentary rock aquifers.

<u>Colorado Plateau Region (southeastern margin of San Juan Basin)</u>

The Colorado Plateau in Sandoval County consists of a large, uplifted block grading toward the center of the San Juan Basin to the west, and consists of the westernmost part of Sandoval County, bounded to the north, west and south by the county line and to the east by the Sierra Nacimiento-Laramide Uplift and the Rio Puerco Fault Zone regions (Fig. 24, oversize version in Appendix A). It marks the southeastern margin of the San Juan Basin. There are no perennial streams in this part of the Colorado Plateau, except for a few short intermittent spring-fed reaches. Streams are ephemeral with their greatest flows during the monsoon. Some of the ephemeral streams are perennial in their headwaters in the Sierra Nacimiento and San Pedro Mountains.

The region is sparsely populated, with the largest community being Cuba along the eastern regional boundary. Surface land uses are mainly rangeland operations (i.e., ranching). As summarized in the first portion of this report, this part of the Colorado Plateau has seen extensive oil and gas development, especially in its northern half. The land ownership is a combination of federal BLM, tribal, state and private properties.

While the oil and gas geology of the Colorado Plateau has been summarized in many major reports, there are only a handful of regional hydrogeologic studies, including Stone and others (1983), Kernodle (1997) , and Kelley and others, (2014), with a stratigraphy laid out in Stone and others (1983) and Craigg (2000). This sparse coverage is in large part due to its sparse population and poor water well coverage. Most recently, Kelley and others (2014) summarized the major fresh and brackish water resources in order to constrain the impact of unconventional oil and gas operations on water availability through the broader San Juan Basin. We summarize the Tertiary and younger hydrostratigraphy in Figure 28. , Figure 3fsummarizes the stratigraphy of the older aquifer units.

Description of aquifers

The primary aquifers in this region are in shallow alluvial aquifers of stream valleys and alluvial fans coming out of the Sierra Nacimiento and San Pedro Mountains, and in the Ojo Alamo Formation. In the far southwestern part of the region, Stone and others (1983) and Kernodle (1997) claimed that the Cretaceous Gallup Sandstone and the Jurassic Morrison Formation as productive aquifers; this is true in the eastern and southern edges of the San Juan Basin, but the well coverage in the western Sandoval County is too sparse to confirm this (Figs. 25-27, oversize versions in Appendix A). Secondary aquifers used for distributed livestock tanks and small domestic wells are generally developed in sandy intervals of the shallowest geologic formations. This includes the San Jose Formation and Nacimiento Formation in the northern part of this region, the various Cretaceous sandstones present at the surface (Pictured Cliffs, sandstones in Menefee Formation, the Cliff House Sandstone, the Point Lookout Sandstone, and the Dakota Sandstone), and in the Agua Zarca Member of the Triassic Chinle Formation (Figs. 25, 26; Stone and others, 1983; Kelley and others, 2014).

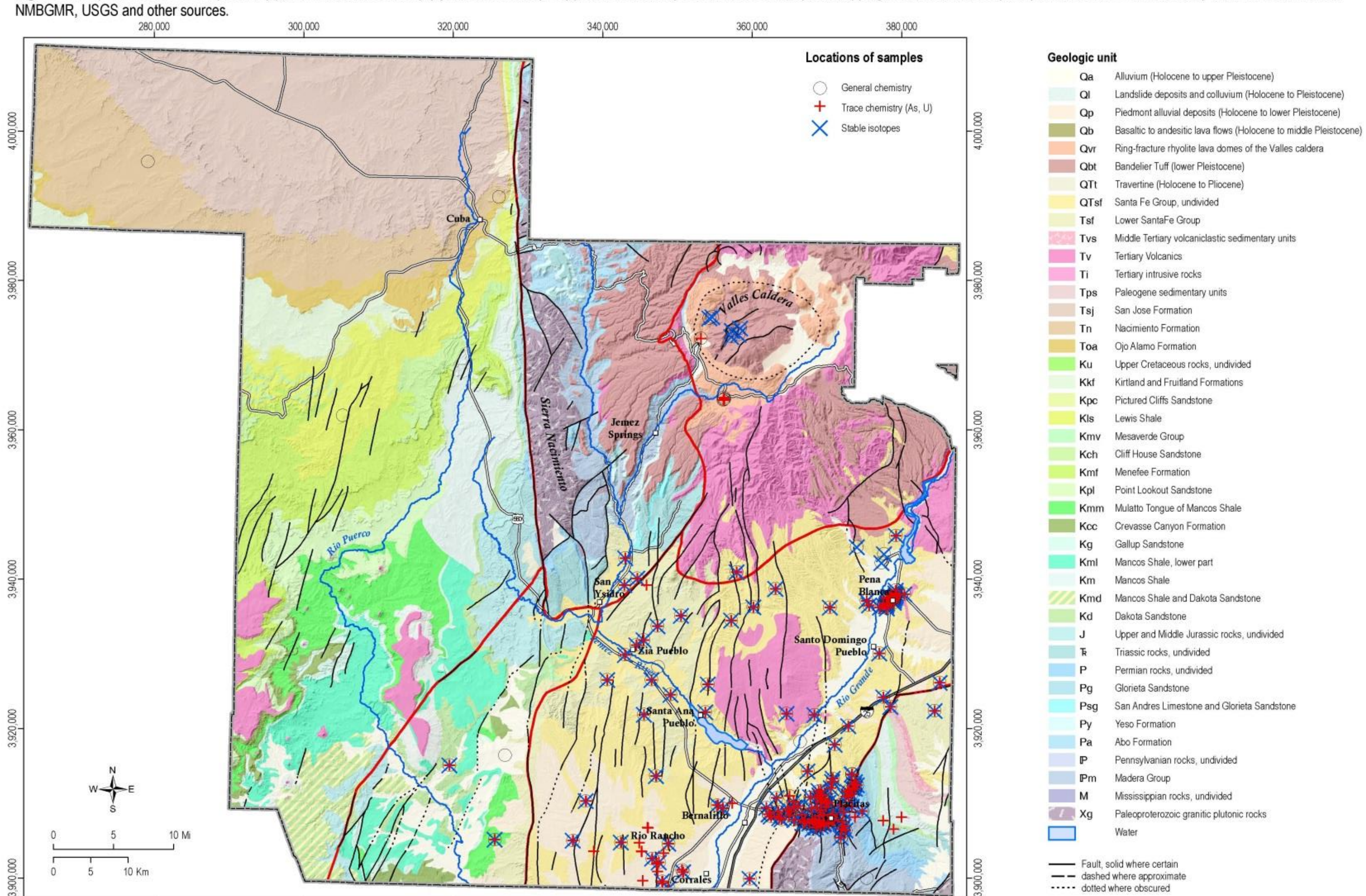
Many of the small communities of the northeastern part of the Colorado Plateau region use groundwater from shallow alluvial aquifers and the Ojo Alamo Formation (Stone and others, 1983). The shallow alluvial aquifers generally have good water quality and up to 200 ft of thickness. The Ojo Alamo Formation ranges from 70 to 135 ft in the region (Fig. 28). This coarse sandstone with thin interbedded clay beds is a good aquifer with reasonable TDS (Stone and others, 1983; Kernodle, 1997; Kelley and others, 2014). However, communities have found that the aquifer can be high in iron, leading to poor water quality (Anderholm, 1979).

The wells within the above Tertiary aquifer units and the alluvium are completed at relatively great depths, ranging from roughly 100 ft bgs to 1500 ft bgs (Fig. 25), but, with a few exceptions, their water tables are shallow (<100 ft) near the base of the Nacimiento Mountains, in the San Jose Formation and in alluvial fill (Fig. 26). In the Nacimiento Formation to the south of the San Jose Formation, water levels are lower and wells tend to be slightly deeper, likely penetrating into the Ojo Alamo Formation (Fig. 26).

In the southern part of the Colorado Plateau region, wells are completed either in Cretaceous sands, in fractured volcanic rocks, or in alluvial fill. Wells along the Rio Puerco and in other canyons tend to be shallow (<200 ft completions; Fig. 25) and have shallow water levels (Fig. 26). However, in the Cretaceous section and away from the valley bottoms, wells become deeper (800 ft or more) and the aquifer is artesian (water levels above ground surface).

Stone and others (1983) showed that salinity correlates most strongly with distance away from the recharge source and, to a lesser extent, with formation. However, near the uplands and streams where recharge occurs, water tends to be relatively fresh in most of both primary and secondary aquifer formations in this region of Sandoval County. There were exceptions,

Figure 27. Map of locations of sampled for (o), trace element chemistry (+) and stable isotopes (x). Water chemistry is from NMBGMR Aquifer Mapping Database, and compiled published values and internally measured values from NMBGMR, USGS and other sources.



Age	Stratigraphic Unit	Description	Thickness (ft)
Pleist. to modern	alluvial deposits	Moderately sorted, tabular to trough cross-bedded silts, sands and gravels with interbedded clay lenses.	0- 200 ft
Eocene	San Jose Formation	Interbedded sandstones and mudstones. Sandstones range from local beds to relatively thick (100-200 ft) members. Mudstones are interbedded with siltstones and poorly consolidated sanddstones.	300 to 1700 ft, thickening to the north
Paleocene	Nacimiento Formation	Primarily a black to gray mudstone, locally containing lignite and carbonaceous mudstone. Increasingly common thin, local, medium-to coarse-grained sand-stone beds to the north.	600 to 1200 ft, thickening to the north
Paleocene	Ojo Alamo Formation	Sequence of sandstone and shales. Sandstone is brown, medium- to very coarse-grained, locally pebbly, deposited in sheetlike sequences. Thin shale beds are locally interspersed.	70 to 135 ft
	Cretaceous and older rocks	See oil and gas assessment. Can be used as aquifer for domestic and livestock in outcropping sandstones.	

Common aquifer formation; Local aquifer formation; Conformable contact; Unconformable contact

Figure 28. Stratigraphy of major Tertiary aquifer units in Colorado Plateau region, adapted from Stone and others (1983) and Craigg (2000).

documented in Stone and others (1983), where extremely saline water was found near recharge areas. These are likely caused by upwelling water along faults.

This region has not been the subject of many water quality studies after Stone and others, (1983) and Phillips and others (1986), partly limited by the lack of wells in this region. Few general water chemistry, trace element chemistry, stable isotope or other studies have been done here, especially at a sub-regional level. Phillips and others (1986) did find that the water flowing through the different, mostly Cretaceous and older aquifers throughout the regional San Juan Basin are evolving (increasing in salinity) meteoric waters that recharged in the uplands encircling the basin. Kelley and other (2014) showed that across the San Juan Basin, good water quality in the subsurface mostly correlated with nearness to recharge locations and shallowness. Consistent with Stone andother (1983), however, there was significant scatter in these results.

Summary and Implications for Oil and Gas Development

This region has been heavily developed for oil and gas in the last 60 years, including conventional operations near streams, towns and domestic wells. While it is difficult to judge the effects of oil and gas operations on water quality simply because of the sparsity of wells and springs in the region, the region has relatively low susceptibility: the targets for petroleum development are deep and have a large thickness (>2000 ft) of impermeable rock between the reservoir and the aquifers, which are mostly relatively shallow. Additionally, the aquifers are confined at depth, with significant head differences between them (Kernodle, 1997). This, too, implies that water supplies are relatively unsusceptible from subsurface contamination. Surface contamination and contamination associated with old boreholes is still a concern, given the relatively shallow water tables in the unconfined portions of the system. An integrated water chemistry study may be able to better assess the impacts of further development, but there has already been so many decades of operations and the system is surrounded by source rock so it would be difficult to assess the difference between naturally evolving water chemistry and possibly contaminated waters.

Rio Puerco Fault Zone

The Rio Puerco fault zone region forms the transition region from the Colorado Plateau region to the Albuquerque Basin region. We defined it as the region between the Nacimiento Fault and its southern extension in the east, and the last fault trace west of a series of closely spaced faults. There are no perennial streams in the region (Fig. 24, oversize version in Appendix A). The major stream is the Rio Puerco, which is sourced from the San Pedro Mountains to the north and flows primarily during large monsoonal rainstorms.

The region is extremely sparsely populated. The largest community is San Ysidro (Fig. 24). The remaining land is largely tribal and federally owned-public land that is used for rangeland.

Hydrogeologic data in this region is sparse. The primary information regarding aquifers in this region is from Stone and others (1983), and in Craigg (1992). Essentially, the same Cretaceous and older aquifers described in the Colorado Plateau are present here, except the Tertiary units and many of the younger Cretaceous units are missing. The aquifers are thought to primarily be in fractured bedrock and recharged locally. Possible aquifers include fractured volcanic rocks, Cretaceous sand bodies, fractured Cretaceous shales, the Dakota Sandstone and the Morrison Formation (Stone and others, 1983). Additionally, the Agua Zarca Sandstone of the Chinle Formation is present and may act as a fractured aquifer (Stone and others, 1983).

One complication is the presence of carbonic springs along the Nacimiento Fault at the northern end of the province (McGibbon, 2015). While these waters are not of drinking quality, the springs bubble with CO_2 and are formed in the Agua Zarca Sandstone of the Chinle Formation (McGibbon, 2015). These springs indicate that the fault zones in the Rio Puerco Fault Zone region can act as high transmissivity conduits at depth, probably sourced from the Jemez Volcanic Field.

Relatively few wells have been drilled in this region, away from San Ysidro. Around San Ysidro, most of wells are completed in the alluvium of the Jemez River. This alluvium forms a relatively high yield aquifer (Craigg, 1992) with shallow (<50 ft) water tables (Fig. 25). Most wells are completed at depths of less than 200 ft bgs. Deeper wells are completed in the Agua Zarca Sandstone near San Ysidro (Fig. 24). Similarly, little is known about the water quality in this region because of the lack of wells and the lack of springs.

Summary and Implications for Oil and Gas Development

This region has an unknown contamination susceptibility to unconventional oil and gas development, but has low oil and gas potential. However, the presence of closely spaced conductive faults, a well-connected fault transmitting CO_2 and water from an unknown distance in the northern end of the region, and, where there are wells, relatively shallow water levels in aquifers neighboring possible source rock all suggest that caution should be used before oil and gas development commences—the reservoir may not be sealed.

Albuquerque Basin

The Albuquerque Basin in central New Mexico is one of the largest basins in the Rio Grande rift that stretches from the San Luis valley of southern Colorado into Mexico and Texas (Chapin and Cather, 1994) and is filled with sediments derived from surrounding uplifts (Figs. 29-30). In Sandoval County, the Albuquerque basin forms one of the largest of the defined regions and, because of its high population, one of the most important in this study. The Albuquerque Basin in Sandoval County is bounded to the west by the Sand Hill/Nacimiento Fault at the Rio Puerco Fault Zone transition, bound to the east by the Sandia Mountains and the Hagan Embayment, along the Sandoval County boundary in the south, and by the Jemez Volcanic Field and the La Bajada Constriction at Cochiti Dam to the north (Figs. 24, 31; Grauch and Connell, 2013). Formed by normal, or extensional, faults that developed a deep basin that has been filled with a combination of fluvial, alluvial, piedmont, lacustrine and eolian sediments (Figs. 31, 32), the basin is at its thickest in the center (~8000 ft of basin-fill; Fig. 33), and shallows and eventually pinches out to the east and west (Hawley and Haase, 1993; Connell, 2008b; and Grauch and Connell, 2013). Internal to the Albuquerque Basin in Sandoval County, there are four major structures: the Calabacillas sub-basin, the Ziana Uplift (or anticline), the Santo Domingo sub-basin, and the La Bajada Constriction (Fig. 33). The sub-basins form the thickest deposits, with thinner basin-fill deposits in the Ziana Uplift and La Bajada Constriction (Fig. 33).

Age	Stratigraphic unit		Description		Thickness (ft)
0 ka - 640 ka	alluvial deposits	river terrace deposits	Moderately to poorly sorted fine- to coarse grained sands with gravel lenses and mud bodies.	Coarse sands and gravels with some muddy layers (up to 20 ft thick).	0–200 ft
700 ka - 4.9 Ma	Sierra Ladrones Fm., Piedmont	Sierra Ladrones Fm., Axial River	'Clean' sands and gravels against mountain front, fining with distance from mountain. Commonly silt-sand-gravel mixed deposits interlayered with muds and sand layers.	Primarily gravely sands with silty gravely sands present in places, pale grey in color with well rounded quartsite clasts. clasts.	900–1,700 ft
5.9–19 Ma	Older Santa Fe Group, Piemont	Older Santa Fe Group, Fluvial	Similar to the piedont Sierra Ladrones Formation, but more cemented and finer grained.	Similar to axial Sierra Ladrones Formation, but with more cements and finer grain-size.	1,600 to 6,900 ft, with deepest regions in center of basin.
37–20 Ma	Unit of Isleta Well #2		Purplish red to gray, volcanic-bearing well-sorted, quartz-rich sandstone with mudstone interbeds and common volcanic beds. Only found in subsurface.		1,500 ft
??–37 Ma	Galisteo Formation		Variegated (multi-colored) interbedded mudstone (50%), sandstone (30%), conglomerate (15%) and siltstone (5%) in large		900 ft to 1,600 ft, thickening from west to east into Hagan Embayment
	Cretaceous and older rocks		See oil and gas assessment.		

Common aquifer formation. ____ Conformable contact _ _ _ Unconformable contact _?_ Unknown type of contact

Figure 29. Hydrostratigraphy of northern Albuquerque Basin, west of Rio Grande, adapted from Connell (2001), Connell and others (2007a,b), and Connell (2008a,b),

Age	Stratigraphic unit	Description	Thickness (ft)
0–100 ka	**alluvial deposits**	Moderately sorted, tabular to trough cross-bedded silts, sands and gravels with interbedded clay lenses.	0–200 ft
1.2–5 Ma	**Ceja Formation**	Pinkish medium to thick-bedded fine-tovery coarse cobbly sand, interbedded with yellowish-red clay. Partly age-equivalent to Sierra Ladrones Formation.	200 ft thickening eastward to 300 ft.
9.8–5.8 Ma	**Arroyo Ojito Formation**	Light brown to reddish yellow sandstones and sandy conglomerate interbedded with brownish muddy sand-stones to muds, that coarsens upwards from sands and muds, to cobbles and boulders and muddy sands.	1,400 to 1,500 ft, relatively constant thickness.
14.6–9.8 Ma	**Cerro Conejo Formation**	Pale brown to pink and yellowish red, well sorted, fine-to medium-grained sandstone with minor mudstone intervals and abundant altered volcanic ash beds.	800 to 1,150 ft,
19.5–16.4 Ma	**Zia Formation**	Composed of three units: Fine-grained,cross-bedded sandstone with intermittent mudstone beds, overlain by a unit with fine-grained sandstones, silty sandstones and siltstones. Capped by unit of interbedded mudstones, fine-grained sandstones and limestones.	980 to 1,300 ft, thickening eastward into basin.
37–20 Ma	**Unit of Isleta Well #2**	Purplish red to gray, volcanic-bearing well-sorted, quartz-rich sandstone with mudstone interbeds and common volcanic beds. Only found in subsurface.	0–1,500 ft, thicken-ing from west to east into the basin.
??–37 Ma	**Galisteo Formation**	Variegated (multi-colored) interbedded mudstone (50%), sandstone (30%), conglomerate (15%) and siltstone (5%) in large	900 ft to 1,600 ft, thickening from west to east into Hagan Embayment
	Cretaceous and older rocks	See oil and gas assessment.	

Common aquifer formation. ____ Conformable contact _ _ _ Unconformable contact _ _?_ Unknown type of contact

Figure 30. Hydrostratigraphy of northern Albuquerque Basin, east of Rio Grande. Summarized from Lozinsky (1994), Connell (2001), Dethier and Sawyer (2006), and Connell (2008a,b).

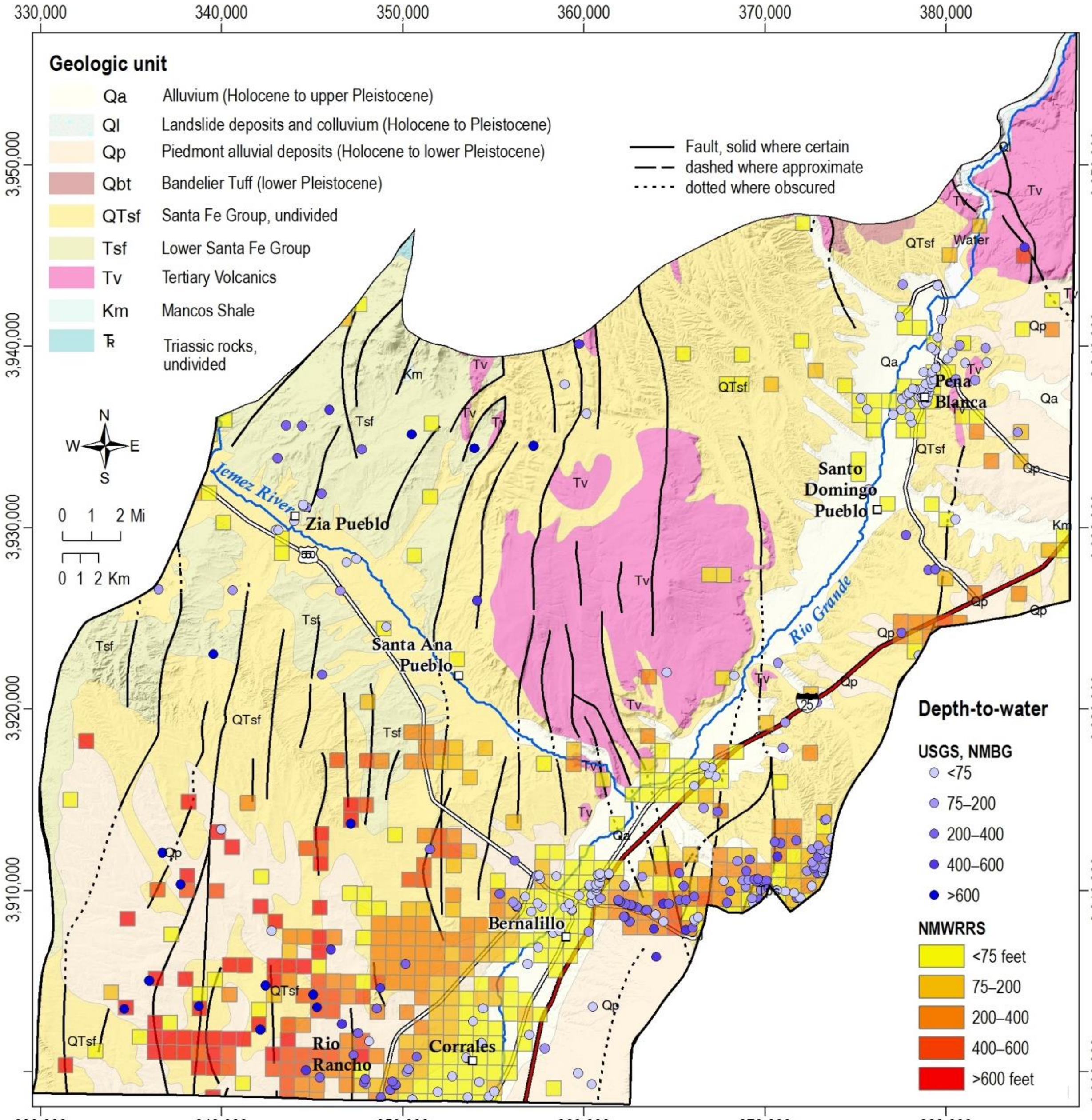


Figure 31. Map of geologic units and structure of northern Albuquerque Basin from simplified geology of NMBGMR (2003) with well depth-to-water from most recent measurements from NMBGMR, USGS and Bernalillo County.

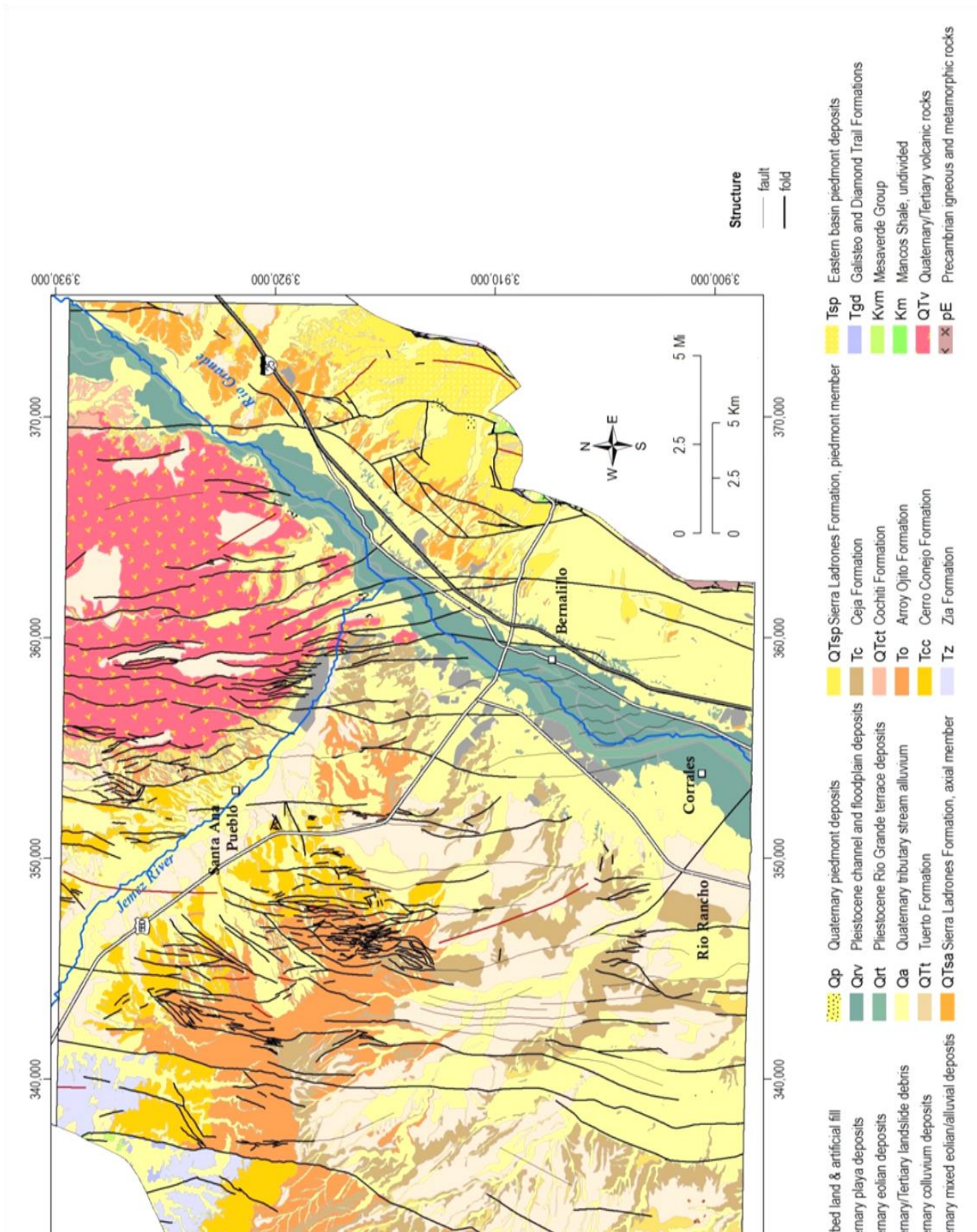


Figure 32. Geologic map of Albuquerque metropolitan area in Sandoval County simplified from Connell (2008b).

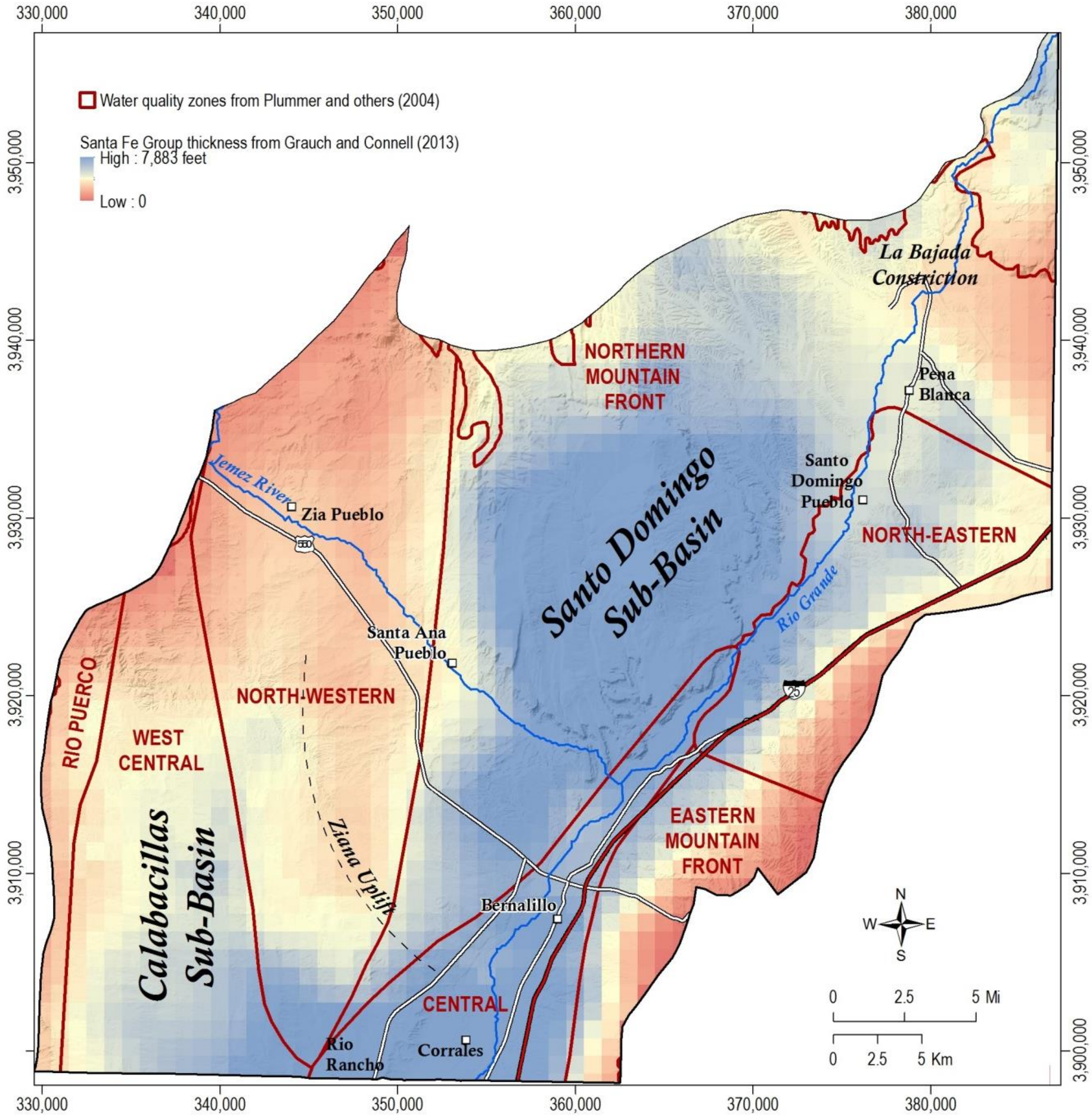


Figure 33. Approximate thickness of Santa Fe Group in the northern Albuquerque Basin with major structural zones (black labels), adapted from Grauch and Connell (2013), and hydrochemical zones (red labels) adapted from Plummer and others (2004).

The Albuquerque Basin has the highest population and population density in the county. Importantly, the community of Rio Rancho straddles the Ziana Uplift, with its western boundary in the northern tongue of the Calabacillas sub-basin and its northern and eastern boundary in the Santo Domingo sub-basin (Fig. 33; Grauch and Connell, 2013). Most of the other communities fall in the Santo Domingo sub-basin (Fig. 33). All of these communities largely, or entirely, rely on groundwater for their drinking water. Away from the cities of the Rio Grande valley and the pueblos, population is sparse though there are several large subdivisions that have been prepared for construction. Land-use is a mix of existing and proposed subdivisions, rangeland and irrigated agriculture. Ownership is a mix of private and tribal lands along the valley, and a mix of private, federal BLM and forest service, and tribal lands outside of the river valley.

The Albuquerque basin has two perennial rivers and many good sized ephemeral tributaries (Fig. 24). The perennial Rio Grande flows through the Albuquerque Basin, while the semi-perennial Jemez River drains into the Rio Grande in the northern part of the region. Both rivers are controlled, with the Rio Grande managed by the Middle Rio Grande Conservancy District for irrigation diversions and the Albuquerque-Bernalillo County Water Authority for a surface drinking water supply. The Jemez River is dammed largely for flood control purposes. Both the mesa around Rio Rancho (i.e., the West Mesa), and the surrounding mountains (Jemez Mountains and Sandia Mountains) feed large ephemeral arroyos that flow largely due to flash floods during monsoon seasons. There are few springs in the region, with some of the springs precipitating travertine mounds that indicate deep flow paths (Plummer and others, 2004).

Because of the its large population, the Albuquerque Basin has been the subject of extensive geologic (Hawley and Haase, 1992; Lozinsky, 1994; Connell, 2001, 2004, 2008a, 2008b; Rawling and others, 2001; Connell and others, 2007a, 2007b; Dethier and Sawyer, 2006; Grauch and Connell, 2013), hydrogeologic (Hawley and Haase, 1993, Bexfield and Anderholm, 2000; Johnson and Campbell, 2002; Powell and McKean, 2014; Rieseterer and others 2003, 2008; Riesterer and Drakos, 2008; Sawyer and Minor, 2006 ; Williams and others, 2015; Rinehart, 2016), and hydrochemical (Plummer and others, 2004) studies. For the northern Albuquerque Basin in Sandoval County, much of that work has been summarized in Connell (2001), Connell and others (2007), Connell (2008a,b), Grauch and Connell (2013), Hawley and Haase (1992), Plummer and others (2004), Bexfield and Anderholm (2000); Powell and McKean (2014), and Sawyer and Minor (2006).

Description of aquifers

The primary aquifers in the Albuquerque are basin-fill sediments associated either with the Plio-Pleistocene ancestral Rio Grande along the center of the valley, Plio-Pleistocene coarse piedmont deposits near the Sandia Mountain base, or Miocene to Pliocene deposits from the ancestral Rio Puerco that drained the Colorado Plateau and Sierra Nacimiento west of the Rio

Grande (Figs. 31, 32; Hawley and Haase, 1992, and Connell, 2008). Secondary aquifers include fractured Pennsylvanian and Permian limestones, volcanic rocks, Rio Grande Pleistocene terrace fills and alluvial valley fills—these aquifers are distant from major population centers and are generally used for domestic and livestock supplies. Additionally, some low-yield wells have been installed in the late Holocene Rio Grande valley fill that caps the deeper basin-fill along the axis of the valley (Hawley and Haase, 1992; Sawyer and Minor, 2006; and Connell and others, 2007).

All of the primary aquifers are in the Santa Fe Group, a general stratigraphic unit demarcating Rio Grande basin-fill sediments (Figs. 29, 30). The highest quality (high storage, high transmissivity) aquifers in the region are associated with the Plio-Pleistocene ancestral Rio Grande deposits, the axial member of the Sierra Ladrones Formation (axial Sierra Ladrones) and the coarsest piedmont member of the Sierra Ladrones Formation (piedmont Sierra Ladrones) of the Upper Santa Fe Group (Figs. 24, 30,32). This aquifer consists of coarse, well-rounded sands and gravels in thick, cross-bedded channel deposits with rare clay lenses from paleo-floodplain deposits (Fig. 32). In the study area, the axial Sierra Ladrones Formation aquifer occurs sub-parallel to the modern river, bounded to the east by large down-to-west faults and piedmont deposits and to the west by large alluvial fans and faults in the La Bajada Constriction and by the terrace risers and older Colorado Plateau ancestral river deposits closer to the southern county line (Fig. 32; Connell, 2008b). The Plio-Pleistocene piedmont deposits along the base of the Sandia Mountains form the piedmont member of the Sierra Ladrones Formation (Figs. 30, 32; Connell, 2008b). While permeability and storage coefficients are more variable than for the axial Sierra Ladrones Formation, the piedmont Sierra Ladrones Formation can be very coarse near the mountain front (Connell, 2004 and 2008a).

Beneath the Sierra Ladrones Formation is the Popotosa Formation, which is a thick series of clay-rich piedmont and playa deposits that filled the northern Rio Grande rift basins before a through-going river formed; these deposits have poor aquifer potential both because of their low permeability but also because of their poor water quality (Hawley and Haase, 1992; Lozinsky, 1994). Below the Popotosa Formation, a sequence of older, low permeability sandstone and mudstones occur, which filled basins formed during the early Rio Grande rift and the middle to late Laramide orogeny; these include the Diamond Trail and Galisteo Formations (Figs. 29, 30).

West of the Rio Grande, the primary high water quality aquifer is in the Arroyo Ojito Formation, a coarse fluvial sand that was deposited by rivers into the basin from the Colorado Plateau (Figs. 29, 32). The Arroyo Ojito Formation is one of several deposits that apparently flowed in from the west and northwest of the Albuquerque Basin. In order of age, the possible aquifers, all from this general provenance, include the Zia Formation, the Cerro Conejo Formation, the Arroyo Ojito Formation, and the Ceja Formation (Connell and others, 2004; and Connell, 2008a and 2008b). Each of these formations has been subdivided into members of various provenance and grain-size (Connell, 2001 and 2008b); for the purposes of this study, we will not consider the members. The Ceja Formation was deposited at approximately the same time as the Sierra Ladrones Formation in the valley center (Figs 29, 30; Connell, 2008b). However, it is generally above the water table in the study area (Figs 29, 31). The Arroyo Ojito Formation was deposited before the Sierra Ladrones Formation, but is located at higher elevations than the axial river sands, and contains most of the aquifer west of the Rio Grande (Fig. 29; Connell, 2008a). In places, the Zia Formation has been drilled for water, though water quality in these very old sands is generally poor (Riesterer and others, 2008). Similar to the eastern part of the basin, there is a considerable thickness of sediment below the Zia Formation in the western part of the Albuquerque Basin (Figs. 29-30; Connell, 2008a and 2008b). It includes the enigmatic Unit of Isleta Well #2 (Connell, 2001, 2004, 2008a, 2008b; Connell and others, 2007b), a 0-2000 ft thick deposit of sand from an unknown source (Fig. 29), and the Galisteo Formation (Fig. 29). Beneath the Galisteo Formation is the eroded top of the Cretaceous rocks (Fig. 29).

Of particular interest, the Albuquerque Basin is cut by a series of faults that appear to compartmentalize some of the aquifers, particularly west of the modern Rio Grande valley (Bexfield and Anderholm, 2000; Riesterer and others, 2003; Plummer and others, 2004; Connell, 2008b; Grauch and Connell, 2013; and Powell and McKean, 2014) . Despite the extensive regional geophysical surveys of the region (see Grauch and Connell, 2013), the geologic nature of these faults is still somewhat enigmatic due to lack of boreholes. From surface exposure, the existing geophysical data, and descriptions of cuttings and geophysical logs of boreholes, there are major faults with offsets of hundreds of meters spaced approximately 1-mi apart across the West Mesa, with areas of older, more cemented rocks exposed along the Ziana Uplift cut by faults with spacing of 100s of meters but with smaller slips (Connell, 2008b; and Grauch and Connell, 2013). It is unclear what effect these faults have deeper in the section on permeability and brittleness (Williams and others, 2015).

The above discussion focused primarily on the Albuquerque Basin in Sandoval County south of the Jemez Mountains. However, there are a number of communities in the southern end of the La Bajada Constriction and the northern end of the Santo Domingo sub-basin. In this region, the primary aquifer is axial Sierra Ladrones Formation sands and gravels, with shallow wells in the Holocene river valley fill (Dethier and Sawyer, 2006; Sawyer and Minor, 2006; and Rinehart 2016).

Well depth and depth-to-water in the Albuquerque Basin vary according to location, with use, and with rock type (Fig. 25, oversize version in Appendix A). West of the Rio Grande, domestic wells (Fig. 35) and most municipal wells are completed at depths shallower than 1000 ft bgs, commonly around 500 ft bgs. The water table is between 200 ft and 400 ft bgs here (Fig. 26, oversize version in Appendix A). Some municipal wells are completed between 1000 ft bgs and 2000 ft bgs (Fig. 25). The deep wells have comparable water levels to the shallower wells around them (Fig. 26). Wells become less and less common to the west of Rio Rancho (Fig. 34, 35). East of the Rio Grande, well depths are generally less than a few hundred feet (Fig. 25) and have shallow (less than 75 ft bgs) water tables. In the valley between the highlands to the east and west of the Rio Grande, wells are shallow (less than

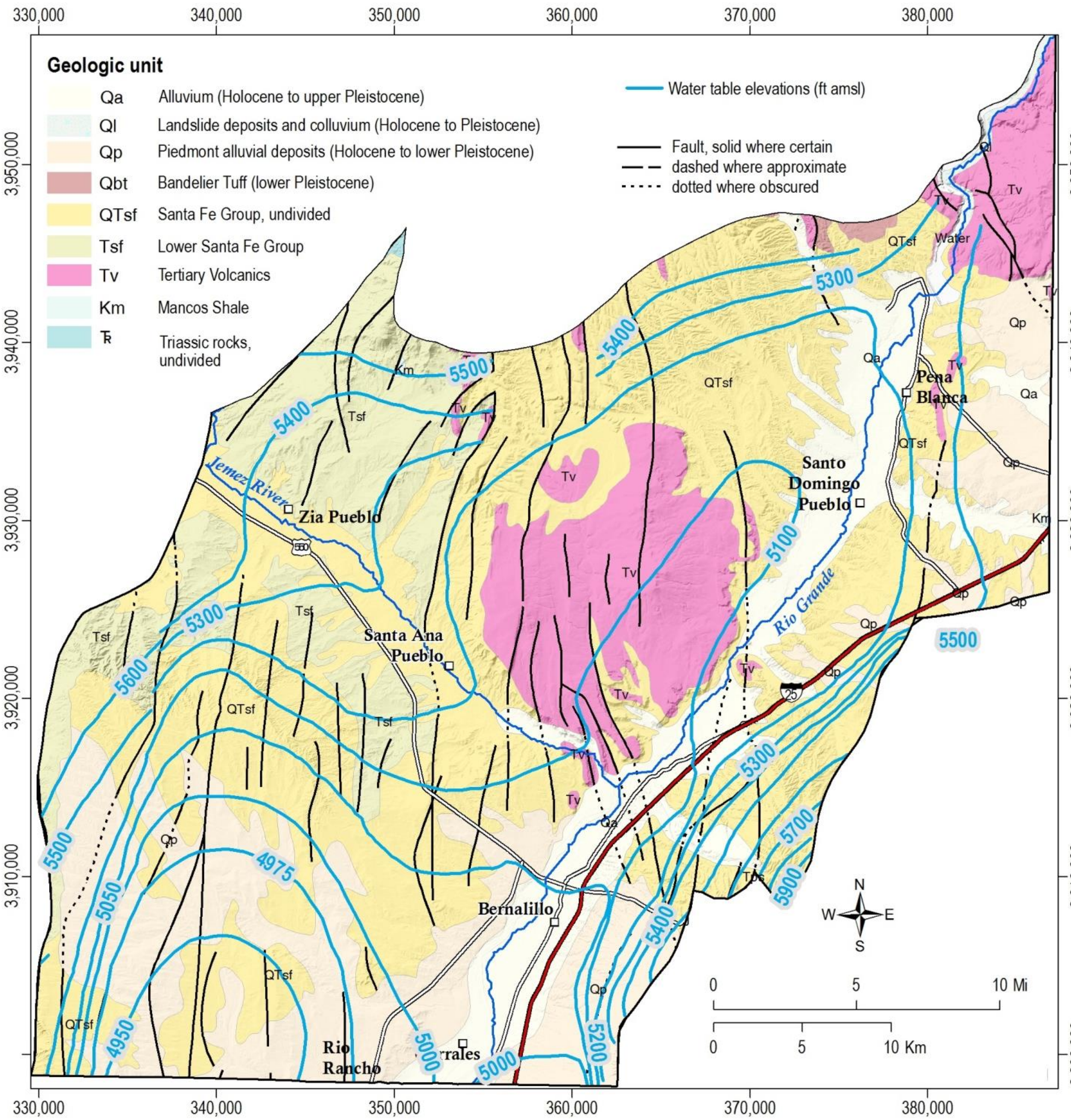


Figure 34. Map of pre-development water table elevations from Bexfield and Anderholm (2000) in the northern Albuquerque Basin.

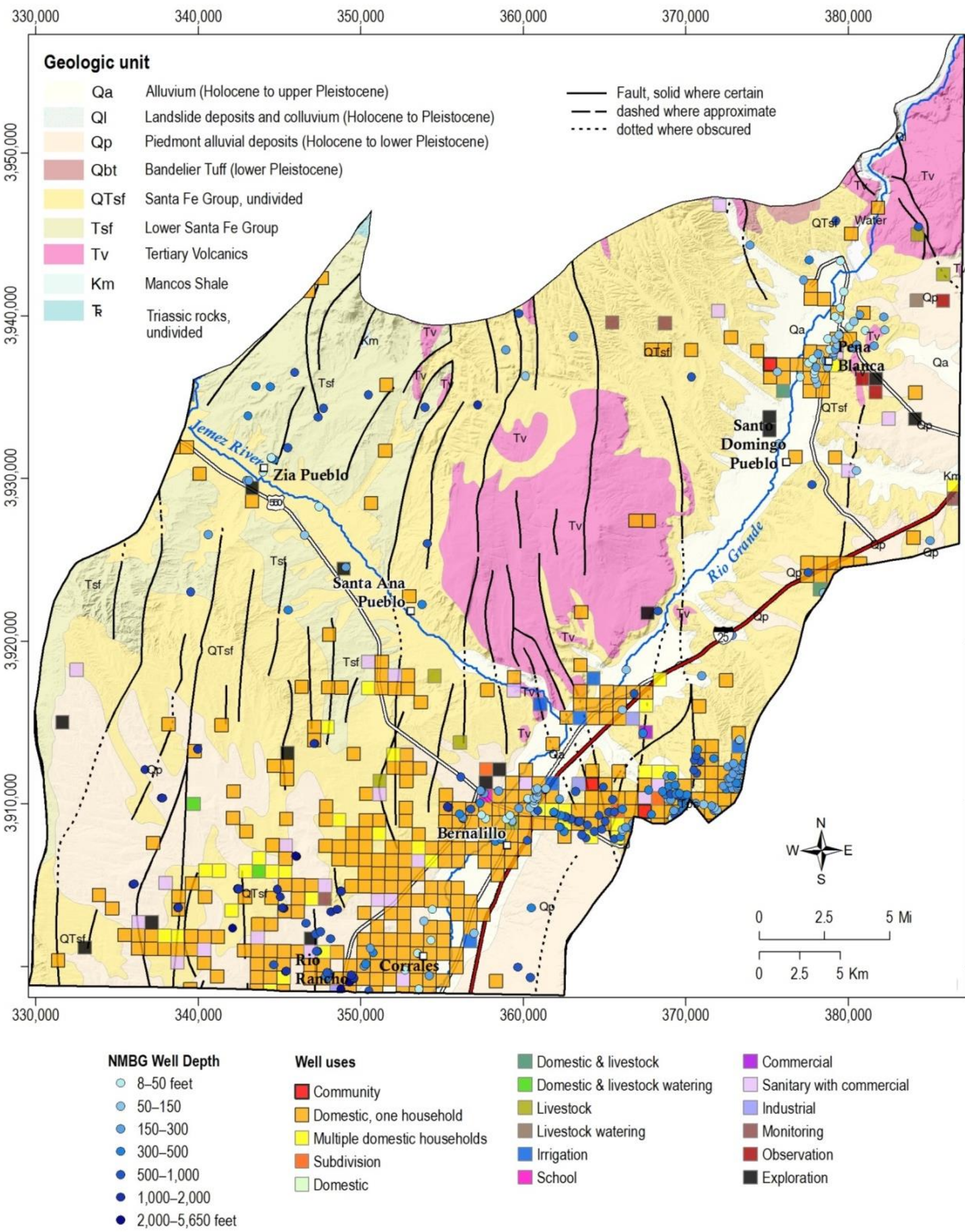


Figure 35. Map of well depth and well use in the northern Albuquerque Basin. Based on New Mexico Bureau of Geology Aquifer Mapping Program database and New Mexico Water Rights Reporting System reported static water levels.

300 ft; Fig. 25) and the water table is very close to the surface (less than 75 ft bgs; Fig. 26). These shallow completion depths and shallow water tables are present throughout the Rio Grande valley.

The pre-development water table elevations (Fig. 34, adapted from Bexfield and Anderholm, 2000) are a conservative surface for understanding the susceptibility of groundwater and surface water to contamination from unconventional oil and gas operations—they show an estimated surface higher than any since the 1950s. Figure 34 shows several broad trends. Groundwater is migrating from the mountain front to the river valleys in all cases, and then transitions to a north-to-south flow parallel to the valley. The Rio Grande in this reach is generally transitions from a gaining to a neutral reach over the study area. The Jemez River is a losing river southeast of Zia Pueblo.

In the west-central and southwestern part of the region, the groundwater is strongly affected by faults (Figs. 31, 32). First, there is a discontinuous water table just east of the region boundary, with a 100-ft drop in water table elevation along a major Quaternary fault (Fig. 34). Then, a 100 ft-deep groundwater ‘trough’ flows from north to south between the faults to the west and the Ziana Uplift to the east. There is a region with higher water table elevations between this trough and the Rio Grande valley. Most City of Rio Rancho wells are completed on this high.

Regions around cities or that have been intensely studied have dense coverage of general chemistry, trace element chemistry and stable isotopes; away from these areas, there is little coverage (Fig. 36). In Figure 33, the hydrochemical zones of Plummer and others (2004)—the single most comprehensive hydrogeochemical survey of the Albuquerque Basin—is overlain on the basin-fill thickness estimates of Grauch and Connell (2013). In the Santo Domingo sub-basin and the La Bajada constriction, groundwater fall in the Northern Mountain Front (Figs. 33, 37; high quality water: low total dissolved solids concentrations and major ions, except for having high SiO_2 concentrations; it is similar to local summer precipitation), the Northeastern zone (Figs. 33, 37; moderate-to-low quality water, with moderately high TDS and high concentrations of uranium), and transitioning into the Central zone (Figs. 33, 37; moderately low TDS with higher concentrations of arsenic). Most of the Ziana Uplift is in the Northwestern zone, which has very low TDS but is high in arsenic. This region also includes wells from northern Rio Rancho, which showed that the upper aquifer system in the Arroyo Ojito and Cerro Conejo Formations had low TDS and high arsenic, but that the underlying Zia Formation was confined and had low TDS with high uranium concentrations (Riesterer and others, 2003 and 2008; and Riesterer and Drakos, 2008). The northern Calabacillas sub-basin is made up of the west-central hydrochemical zone (Figs. 33, 37), which has moderate TDS and high arsenic concentrations. This is the water in the groundwater ‘trough’ of Bexfield and Anderholm (2000) and Plummer and others (2004). It is thought that this water recharged in the Jemez Mountains during the previous Ice Age and is now flowing slowly into the Rio Grande; it is unclear why it is relatively isolated from the Ziana Uplift/Northwestern hydrochemical zone to the east

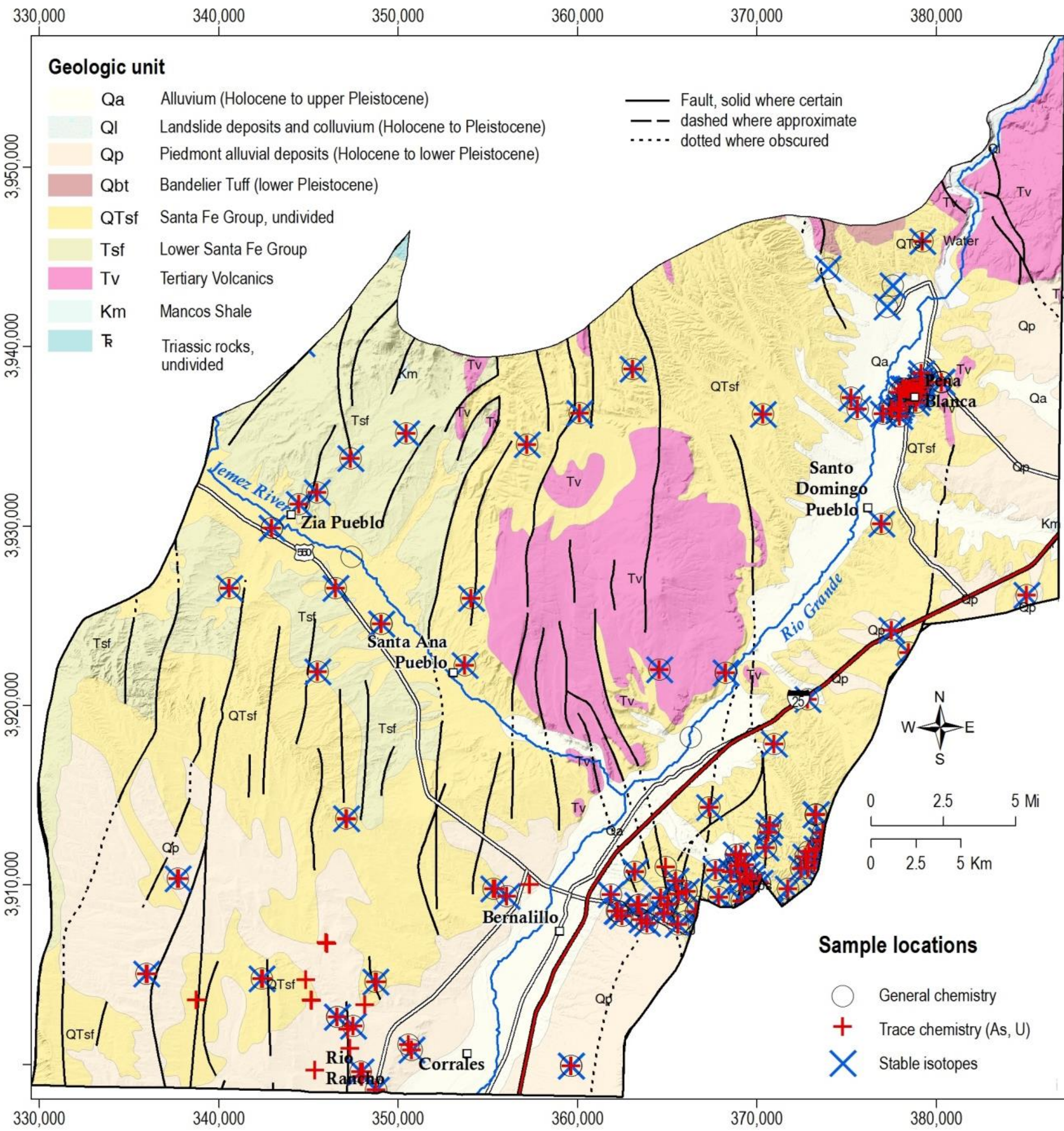


Figure 36. Location of sampled wells and springs in the northern Albuquerque Basin region with general chemistry (o), trace element chemistry (+) and stable isotopes (x) from NMBGMR Aquifer Mapping Database.

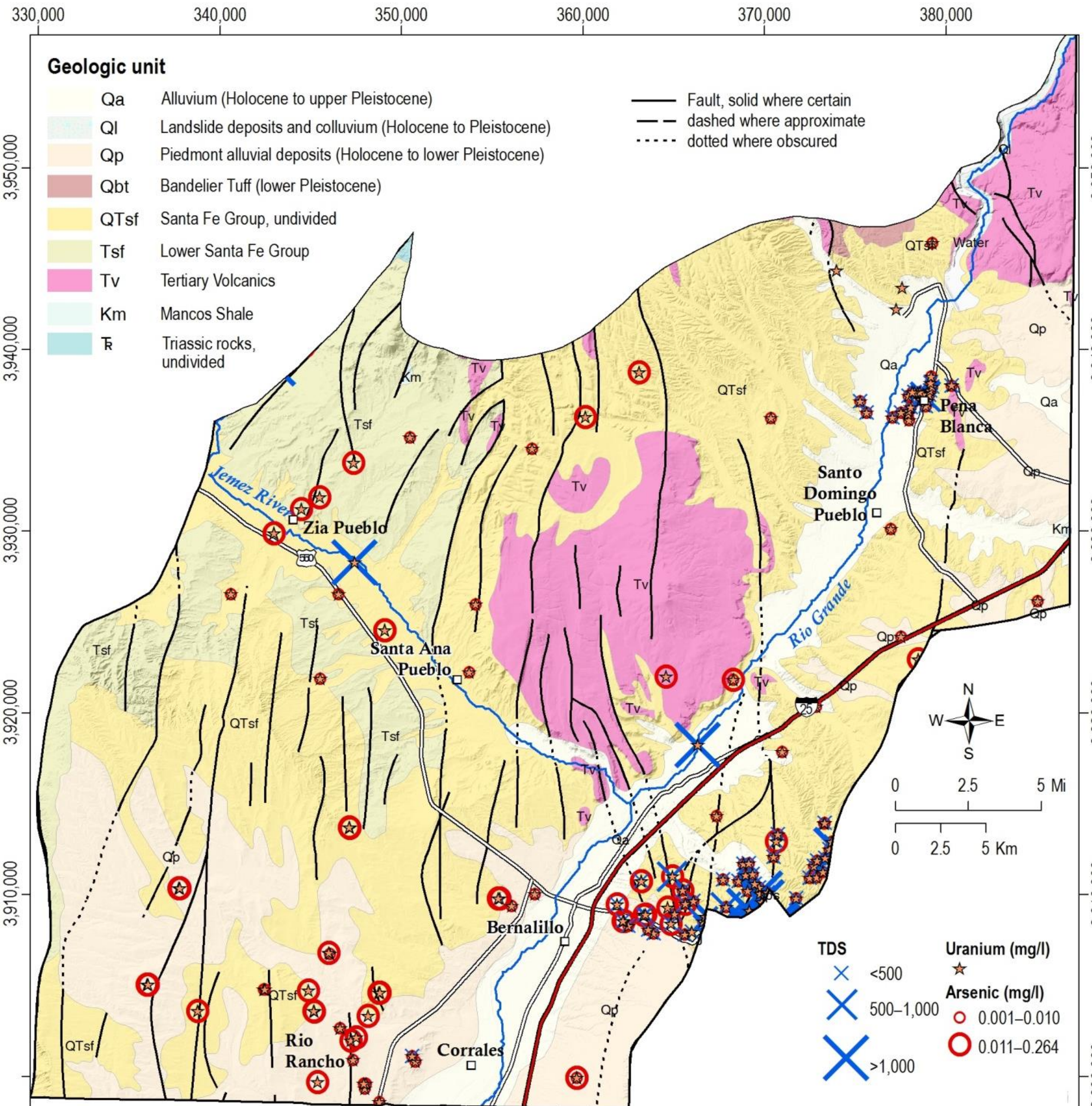


Figure 37. Map of total dissolved solids concentrations, arsenic concentrations and uranium concentrations in the northern Albuquerque Basin region.

(Plummer and others, 2004; Riesterer and others, 2003). The Rio Puerco hydrochemical zone along the western boundary of the area has very high TDS, is relatively high in uranium and most other ions, except for SiO_2, arsenic, barium and vanadium (Plummer and others, 2004). This water is gradually leaking into the basin, but is likely partly compartmentalized (Bexfield and Anderholm, 2000), and is sourced in the Sierra Nacimientos but has interacted with the Mesozoic rocks that the Rio Puerco flows across (Plummer and others, 2004).

In short, most of the water in the Rio Grande region has reasonable to good quality with some areas having high arsenic concentrations. Geochemically, the system shows that it is partly compartmented, consistent with the pre-development water level elevations.

Summary and Implications for Oil and Gas Development

The Albuquerque Basin region is dominated by rift basin-fill aquifers that were sourced by the Rio Grande, piedmont deposits, or large inter-basin tributaries. The primary aquifers are alluvial and recent Holocene fluvial deposits, the Sierra Ladrones Formation in and east of the modern valley, and the Arroyo Ojito and Cerro Conejo Formations west of the modern valley. Thousands of feet of sediment sit between the aquifer formations and the Cretaceous units. These sandstone units have moderate to high permeabilities and do not act as good seals. They do, however, provide water to dilute any upwelling contamination. Below the Cenozoic sediments are the Cretaceous rocks described in the oil and gas portion of this report. The Cretaceous sedimentary rocks are largely shales. There are several thousand feet of Cretaceous rocks with multiple seals between the Mancos C—the likely target—and the Cenozoic rocks. This means that in much of the Albuquerque Basin, there are many thousands of feet of sediment between the aquifers and the shallowest oil and gas reservoirs.

The water table is shallow in valleys, and moderately deep (100s ft bgs) in the uplands. Water quality is generally good, though many regions have high natural arsenic concentrations. The urban areas and a few communities have been the site of intensive hydrogeologic and hydrogeochemical study.

However, the region is densely populated and the vast majority of wells are used for domestic or municipal supply, or, in the valley, for irrigation. While the basin-fill thickness and the existence of multiple seals indicates low susceptibility of contamination from upward flow during oil and gas operations, the high population and well density mean that the area has a high susceptibility to surface contamination during oil and gas operations. Additionally, the reliance of the towns and cities on groundwater implies that pervasive contamination issues could severely impact local drinking water access. This increases the risk to, though not the susceptibility of these regions to surface contamination from oil and gas operations. Development of regions in the Rio Grande Valley and along the Jemez River need to be carefully considered because of their population centers and the shallow groundwater table—the aquifers are susceptible to surface contamination.

Discussion and Summary of Aquifer Distribution and Susceptibility

Sandoval County has a wide range of susceptibilities to groundwater contamination from unconventional oil and gas operations. Each region is distinct and is summarized in the following section. In general, however, the Mancos Shale reservoirs of this region are gravity drained (i.e., at hydrostatic pressure), which, while complicating production, lowers the general susceptibility of the entire region.

The Sandia Mountain-Placitas-Hagan Embayment region has a low susceptibility to contamination, though, similar to the Albuquerque Basin, it is more susceptible to surface contamination than subsurface contamination. There is little oil and gas potential in the region and there are few existing boreholes. Water tables are generally shallow, however, so development needs to be performed mindful of surface contamination issues.

The Jemez Mountains Volcanic Field has little to no oil and gas potential and has low population density, making the overall susceptibility low. There are multiple seals between any possible oil and gas reservoir and the high quality drinking water. However, there is clear communication between the deep subsurface and the shallow aquifers along caldera ring fractures and faults.

The Sierra Nacimiento-Laramide Uplift region also has a low population density with little to no oil and gas potential. There is little thickness of sedimentary rock between the Precambrian core and the surface. The region has few or no petroleum source rocks and thus a low potential, resulting in a low susceptibility. However, surface contamination could be an issue in this region in the unlikely event that wells are drilled. Additionally, faults connecting this region to the Jemez Volcanic Field conduct fluids, implying that any development needs to planned to avoid the regional faults.

The Colorado Plateau/San Juan Basin has a low susceptibility, especially away from water ways and communities, because of the multiple seals between target reservoirs and the aquifers, the depth of water and the low population density. However, this region has a long history of oil and gas development, leading to older oil and gas wells some of which may have problematic casings. These older wells possibly increase the susceptibility of leakage.

Little is known about the hydrogeology of the Rio Puerco Fault Zone. Much of the Cretaceous section has been stripped and the aquifers are generally in alluvium or in shallow Cretaceous sandstones. Water wells are generally relatively shallow and are completed in what are probably local aquifers. The region has a low susceptibility to groundwater contamination because (a) there is little oil and gas potential here, (b) the population density is low, and (c) there is little previous oil and gas development. However, faults should be identified before development, as they appear to act as conduits to flow in the region.

The Albuquerque Basin also has a relatively low susceptibility to subsurface contamination. There are thousands of feet section (combined Cretaceous section above the Mancos C and the early Cenozoic sediments) between the Mancos C and the aquifers in most of the region; in fact, there is generally thousands of feet (5000 to 6000 ft) of rock between the top of the Cretaceous section and the bottom of the aquifer units. Few deep boreholes exist in the region, making leakage up compromised boreholes unlikely. The region is more susceptible to surface contamination, because of relatively shallow water tables, and high population density with dense well networks. Critically, water tables in the Rio Grande Valley are very shallow. Accidental spills during operations in this region could put neighboring water wells at significant risk. Operations around population centers, including Rio Rancho and also the smaller communities, are high risk, given the reliance of all of the communities on groundwater as their drinking water supply. Additionally, there are faults in the region that have acted as conduits to upwelling deep brines before, implying that leakage up faults is a possible, albeit unlikely, contamination pathway.

ACKNOWLEDGMENTS

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