The Oil and Natural Gas Potential Of Sandoval County, New Mexico and it's Relationship to Groundwater: Supplementary Report (Revised)

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INTRODUCTION

In June 2018, the New Mexico Tech assessment of petroleum potential and groundwater contamination risk from unconventional oil and gas development across Sandoval County was delivered to the Sandoval County Planning and Zoning Department in written format. An oral presentation of the study was delivered at a Sandoval County Commission Meeting on July 12. This original work was spurred by a proposed oil and gas exploratory well that was to be located just west of Rio Rancho. During the oral presentation, members of the Sandoval County Commission and the Sandoval County Planning and Zoning Board raised several questions about the groundwater risk assessment that required clarification and enhanced study and also requested additional analysis of oil and gas potential based upon proprietary data that might be received from Thrust Energy. The supplementary report on the oil and natural gas potential of Sandoval County and the relationship of potential to water resources was prepared in response to comments received after the presentation of the main report (Broadhead and Rinehart, 2018). In this supplement, the additional work and clarifications are presented. The Supplementary Report was presented at a meeting of the Sandoval County Commission on October 18, 2018. ***This revised version of the Supplementary Report was prepared at the suggestion of Mike Springfield, Sandoval County Planning & Zoning Division Director, in order to include illustrations that were used in the oral presentation of October 18 but that were not utilized in the original Supplementary Report because of time constraints.***

Specifically this supplement incorporates a more detailed and advanced assessment of oil and gas potential of the Albuquerque Basin. This more advanced assessment of oil and gas potential is based upon a mathematical model and data not utilized in the original report because of time and funding constraints. A numerical model of thermal maturity as well as a method of estimating thermal maturity, and therefore oil and gas potential, in undrilled areas of the Albuquerque Basin is presented and discussed. The clarifications and enhancements pertaining to groundwater risk assessment are also presented. In particular, for both subsurface and surface pathways of contamination, the thresholds between low, moderate and high susceptibility and low, moderate and high risk are justified and made explicit. Discussed in more detail are transmissivity, or lack thereof of faults, fractures and geologic seals in Sandoval County. Further information on the spatial variability of susceptibility and risk is added. Of the two authors of this supplementary report, Broadhead was responsible for evaluation of the oil and gas potential and Rinehart was responsible for the discussion of risk susceptibility and risk thresholds.

PETROLEUM (OIL & GAS) POTENTIAL

The assessment of petroleum potential in the original report was based on the examination of well records and well logs as well as laboratory source-rock analyses of drill cuttings from wells as presented in the source rock database (Sandovalsrcrks.xls) in Appendix B. Although there were pre-existing source-rock analyses on a sufficient number of wells to adequately map thermal maturity in the San Juan Basin, there was only one well in the Sandoval County part of the Albuquerque Basin for which petroleum source rock analyses were available, the Shell No. 1 Santa Fe which was drilled on top of the Zianna Uplift (Figure S1). In this well, there are vitrinite reflectance (R_o) measurements at depths ranging from 4,000 ft to 10,800 ft representing several Cretaceous strata (Menefee Formation, the Mancos A shale, the base of the Mancos B shale, the Juana Lopez Member of the Lower Mancos Shale, shales in the Dakota Sandstone) as well as limestone in the Jurassic Todilto Formation and limestones and shales in the Pennsylvanian Madera Group. Other maturity parameters determined from cuttings of the No. 1 Santa Fe well include the Thermal Alteration Index (TAI) and parameters derived from Rock-Eval pyrolysis. In addition, there have been only three deep exploration wells drilled in the Sandoval County part of the Albuquerque Basin, which limits the accuracy of subsurface geological mapping.

A simple depth-dependent predictive model of thermal maturation was developed based on the R_o measurements from the Shell No. 1 Santa Fe well (Figure S2). R_o was plotted against depth and linear regression was calculated (Figure S3). The resulting regression equation was: $R_p = 0.000102D + 0.036$ where R_p = predicted vitrinite reflectance and D = depth. This simple model was then used to predict vitrinite reflectance, and therefore thermal maturity, in three wells that have not had source rock analyses performed on drill cuttings. This model was also used to predict vitrinite reflectance in areas where no wells are present but where geologic information can be used to estimate the depth to various source rock strata, such as the Mancos

C, which is the principal productive Mancos unit in the San Juan Basin. The model will fail if used in areas with significantly different thermal histories than encountered in the Shell No. 1 Santa Fe well. For example, the intense heating caused by volcanism that formed the Jemez Mountains volcanic field will render the model invalid over the area north of the Jemez River. The model also cannot be used in the southern part of the Albuquerque Basin, an area with significantly higher present-day geothermal gradients than found in the northern part of the Albuquerque Basin.

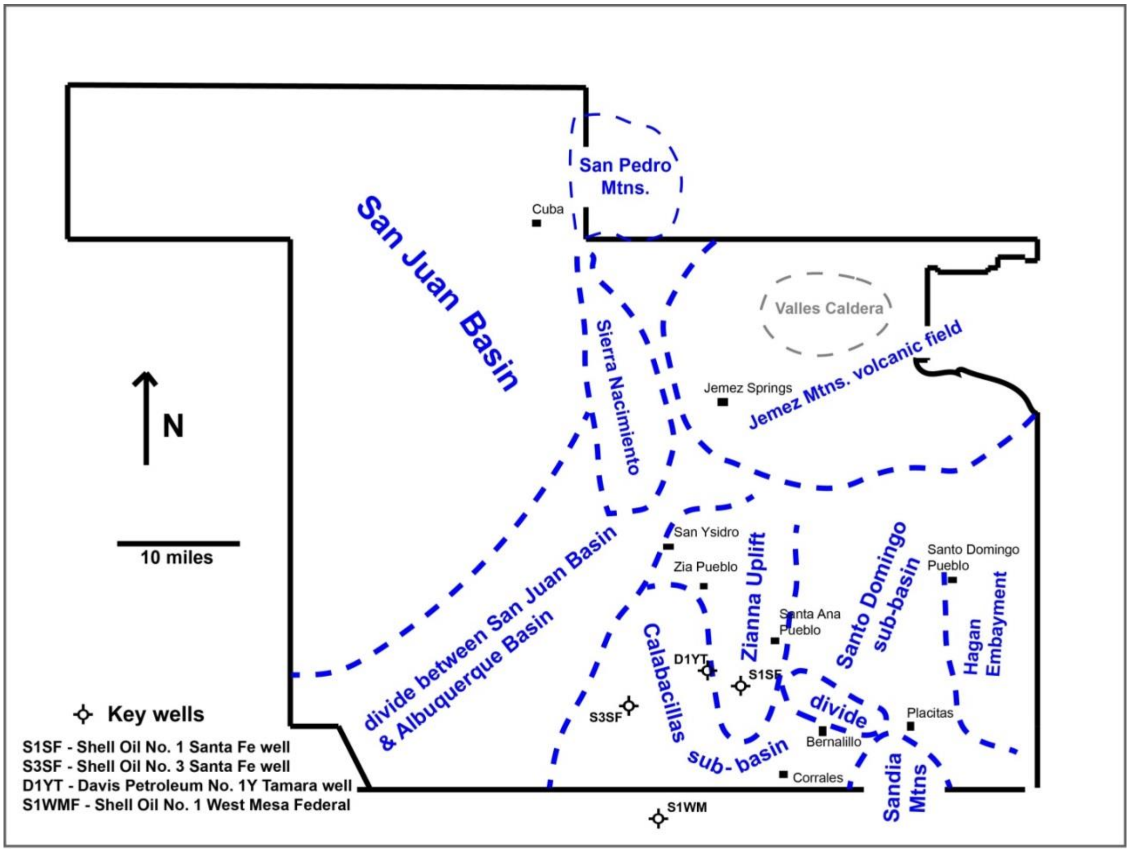

Figure S1. Outline of Sandoval County showing major geologic elements within the county and key exploratory wells within the Albuquerque Basin. The Calabacitas sub-basin constitutes the northern end of the Albuquerque Basin. The Santo Domingo sub-basin and the Hagan embayment are southern extensions of the Española Basin. Outlines of the Calabacitas and Santo Domingo sub-basins modified from Grauch and Connell (2013). Also shown are the locations of the Shell Oil No. 1 Santa Fe well, which has petroleum source rock analyses, and three wells Shell Oil No. 3 Santa Fe, Davis Petroleum No. 1Y Tamara, and Shell Oil No. 1 West Mesa Federal) for which thermal maturity was estimated using the model developed for this report.

Shell Oil Co. No. 1 Santa Fe
Sec. 18 - T13N - R3E

Stratigraphic unit		Depth to top (ft)	R_m Measured vitrinite reflectance	R_p Predicted vitrinite reflectance	Thermal maturity
Lewis		3144		0.36	immature
Menefee		3596	0.50	0.40	
Mancos A & B		4520	0.60	0.50	upper oil window
Mancos C		5420	0.55	0.59	
Lower Mancos Shale	Upper Carlile	5698		0.62	
	Juana Lopez	6094	0.49	0.66	
	Lower Carlile	6238		0.67	
	Greenhorn	6426		0.69	
	Graneros	6492		0.70	uppermost part of lower oil window
Dakota Ss		6600	0.65	0.71	
Todilto		7450	0.89	0.80	

Figure S2. Measured (R_o) and predicted (R_p) vitrinite reflectance for the Shell No. 1 Santa Fe well, located in Sec. 18, T13N, R3E, Sandoval County. Measured R_o data from Bayliss (1998). See Figure S1 for location of well.

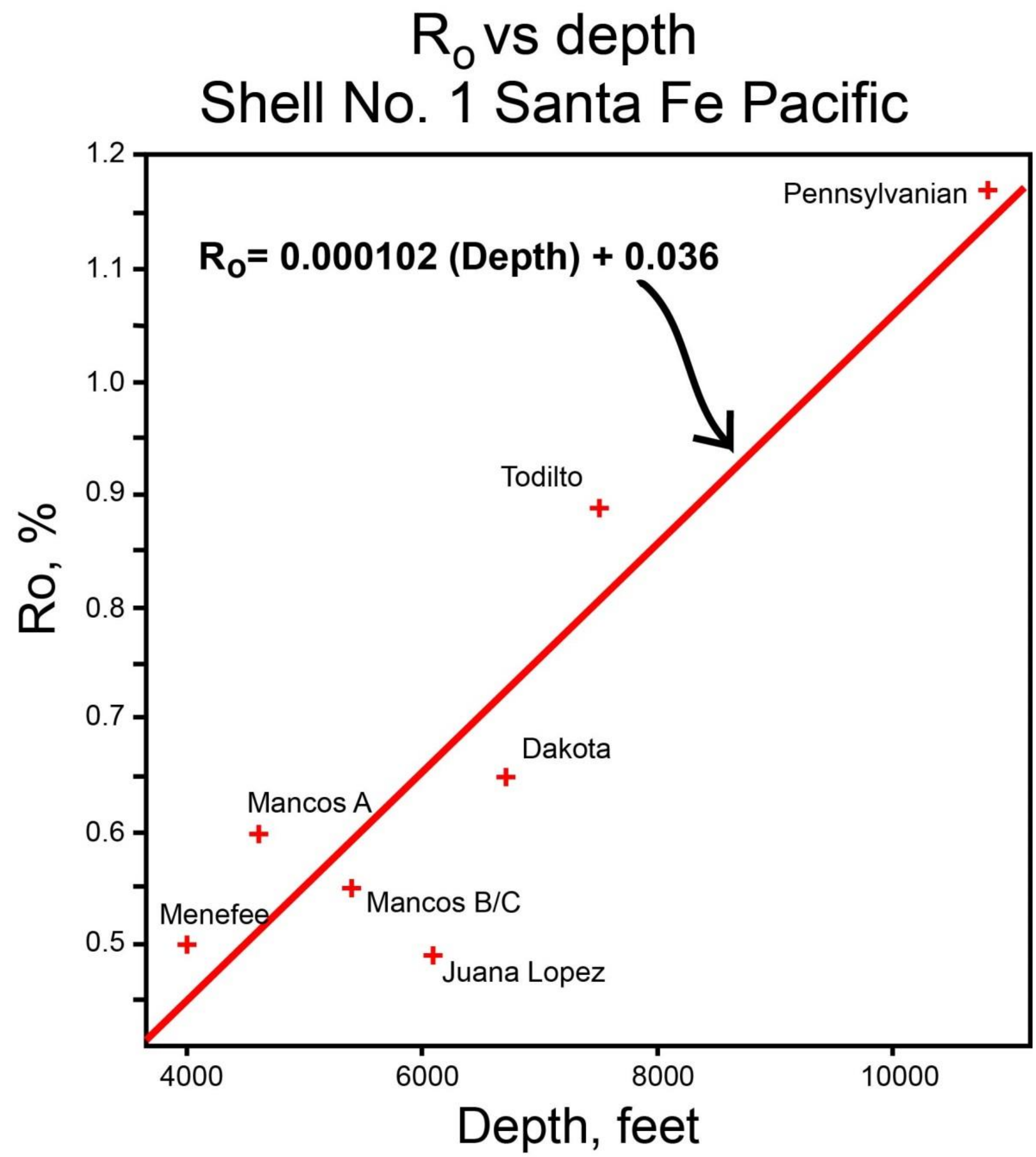

Figure S3. Plot of vitrinite reflectance (R_o) vs. depth for the Shell Oil No. 1 Santa Fe well, located in Sec. 18, T13N, R3E, Sandoval County. R_o data from Bayliss (1998). See Figure S1 for location of well.

One method for describing and illustrating the thermal maturity of a stratum (rock layer) is to plot various indicators of thermal maturity on a petroleum generation profile (Figure S4). In Figure S4, the three indicators are vitrinite reflectance (or R_o), the Thermal Alteration Index (or TAI), and the Rock-Eval pyrolysis TMAX measurement. These indicators are determined from analytical procedures that can be applied to the kerogen in a shale (see inset of Figure S4). Kerogen s are the remains of organic matter which was incorporated into the shale when it was deposited. Kerogens are chiefly the remains of plants such as marine algae and land plants. As a shale is buried more deeply by increasingly thick overlying sediment, it is subjected to increasingly high temperatures. Given sufficient temperature and time, the kerogen in the shale becomes thermally matured (or "cooked") and oil and natural gas are generated. Some types of kerogens, such as algae, will generate oil and associated natural gas upon maturation. Other types, such as the woody parts of trees, will generate gas upon maturation. The top of the oil window marks the point when oil and natural gas first starts to be generated. With further burial, temperature increases and the lower part of the oil window is entered, with increasing volumes of oil and associated gas generated with increasing maturity. At the base of the oil window, the kerogen in the shale has been expended and has generated almost all of the oil and gas it is capable of generating. Equally important, when temperature becomes sufficiently high that generated oil begins to be thermally cracked (or naturally refined) it breaks down into wet gas (chiefly ethane, propane and butane) and dry gas (methane). At yet increasingly high temperatures, the wet gases are broken down into dry gas. This part of the maturation profile is referred to as the thermogenic gas window which, in turn, can be broken down into the wet gas window (above) and the dry gas window (below).

Once the oil and gas have been generated, part of what has been generated is expelled into adjacent reservoir rocks. Conventional oil accumulations can be defined as oil accumulations in which oil has been expelled from a source rock and has migrated into an adjacent conventional reservoir where it will move through the water-filled reservoir rock until it encounters a trap. The conventional reservoir is typically either a sandstone or a limestone.

Unconventional reservoirs may be defined as a reservoir that has very low permeability which limits the amount of oil that can be produced from the rock. Typical unconventional reservoirs, such as the Mancos Shale, are shales that have generated oil and gas or are thin and very fine-grained sandstones that are interlayered with the shale source rocks. Unconventional oil accumulations that are found in shales are mostly found in shales that have been matured to peak oil generation (R_o between 0.9 and 1.0; see Fig. S4). In shale reservoir systems, oil does not migrate (or move) long distances from where it is generated. Although oil may be produced from shales with R_o values as low as 0.6 (upper oil window), optimum resources in most shales have been obtained only where thermal maturation has reached peak oil generation and it is within these more mature areas where shales are intensively developed and produced (for examples see Cardott, 2014 and Clarke et al., 2016). Larger volumes of oil will have been generated where the shale is more mature and the oil will be less dense and less viscous, allowing it to move through the low-permeability unconventional reservoirs.

Oil will not be generated in shales where thermal maturity has not yet reached the oil window. In very shallow strata, however, biogenic gas can sometimes be generated. This gas is not produced from the kerogen in the shale but instead is produced as a part of the metabolism of bacteria that live in the shallow water column (see Shurr and Ridgely, 2002; Martini et al., 1998). As a result, low-pressure accumulations of biogenic gas may sometimes occur or the biogenic gas may be dispersed in unproducible form throughout the water column. In shales, biogenic gas can be found as free gas in the water column within fracture systems, it may be adsorbed onto the kerogen at fracture faces, or it may be migrate into interlayered non-shale rocks such as fine-grained sandstones.

The thermal model developed for this project was used to predict vitrinite reflectance in three wells in the northern Albuquerque Basin (Davis No. 1 Tamara, Shell No. 3 Santa Fe, Shell No. 1 West Mesa; see Figure S1 for well locations) as well as for three areas where wells have not been drilled (the northwestern arm of the Calabacillas sub-basin west of the Zianna Uplift, the southern part of the Santo Domingo sub-basin, and the divide between the Calabacillas and Santo Domingo sub-basins; see Figure 1 for locations of these areas). Of the deep wells present in the Sandoval County part of the Calabacillas sub-basin and the adjoin area in Bernalillo County, R_o measurements were available only for the Shell No. 1 Santa Fe well, which along with TAI and TMAX measurements. In this well, the Mancos C has been matured only to the upper part of the upper oil window and is far short of the thermal maturity needed for a significant oil resource in this unconventional reservoir (Figures S2, S5). For comparison, the petroleum generation profile of the Getty Oil No. 20E Jicarilla B well (Figure S6) located along the main trend of Mancos C production at the southeastern end of the San Juan Basin. In the Getty well, R_o measurements made on cores place the Mancos C within the lower part of the oil window at peak oil generation. Further to the southeast where the Mancos C is not productive in spite of numerous exploratory wells that have been drilled, the Mancos C is thermally immature and has not reached the oil window in the Shell No. 41 Wright well (Figure S7).

The Davis Petroleum No. 1Y Tamara is located on the western flank of the Zianna Uplift and is three miles northwest of the Shell No. 1 Santa Fe well. In this well the major source rock strata of interest are present at depths approximately 1500 ft deeper than in the Shell No. 1 Santa Fe well. As a result, thermal maturity of source rock intervals is higher in the Davis well (Figure S8). The Mancos C has been matured into the upper part of the lower oil window but has not yet attained peak oil generation (Figure S9). Although the lower parts of the Mancos approach peak oil in the Davis well, peak oil generation has not been attained (Figure S8). Oil potential in the Mancos in this well should then be considered low, but higher than in the Shell No. 1 Santa Fe well.

The Shell No. 3 Santa Fe well, located 10 miles west of the Davis well, was drilled just west of the San Ysidro fault. As a result the Shell No. 3 Santa Fe well is located on a shallow, upthrown fault block on the western flank of the Albuquerque Basin (see Connell, 2008, his cross section A-A’). The predicted vitrinite reflectance values in the No. 3 Santa Fe well (Figure S10) falls within the upper parts of the lower oil window in the Mancos C and in the Upper Carlile shale and Juana Lopez Member. The Mancos C has not yet attained peak oil generation in this well (Figure S11). The Greenhorn Limestone, and the Graneros Shale have attained peak oil generation. Therefore these more mature units are assigned a moderate oil potential and the less mature units (Mancos C, upper Carlile shale, Juana Lopez) have a low oil potential or perhaps low bordering on moderate. Note that a moderate and not a high potential is assigned to the most mature units because no wells have tested significant flows of oil which would demonstrate the productive capability of the reservoir. This is unlike the Sandoval County part of the San Juan Basin where the productive capability of Mancos reservoirs, especially the Mancos C, is established.

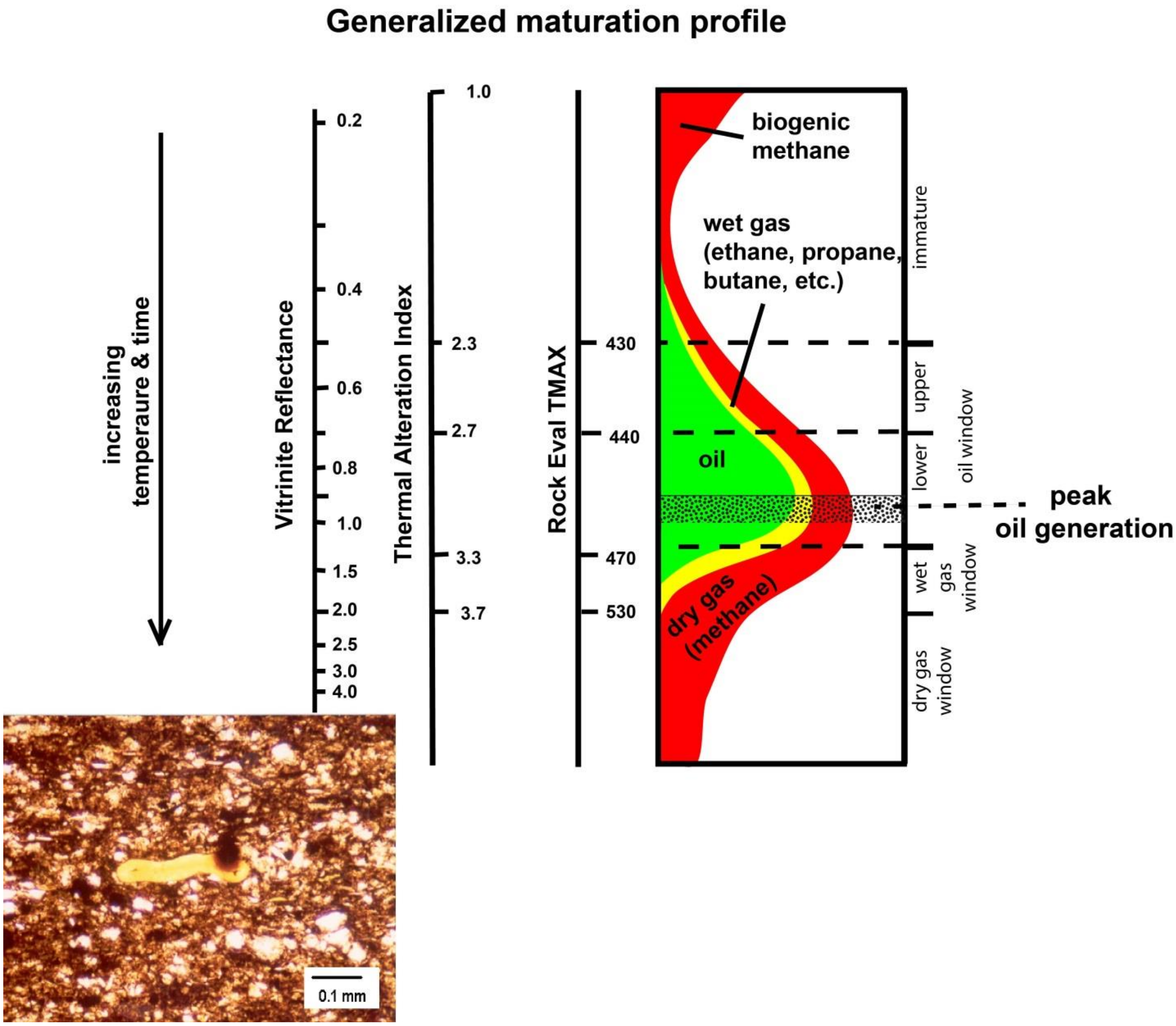

Figure S4. Generic petroleum generation profile showing relationship of oil and gas generation phases in relation to three commonly measured maturation parameters: vitrinite reflectance, Thermal Alteration Index, and Rock-Eval TMAX. Inset is a highly magnified photograph of a source petroleum source rock. The window of peak oil generation is indicated by the stippled pattern on the profile. Thermal maturation profile adapted from Geochem Laboratories, Inc. (1980), Tissot et al. (1974), Mukhopadhyay (1994), Senftle and Landis (1991), and Huc (2013).

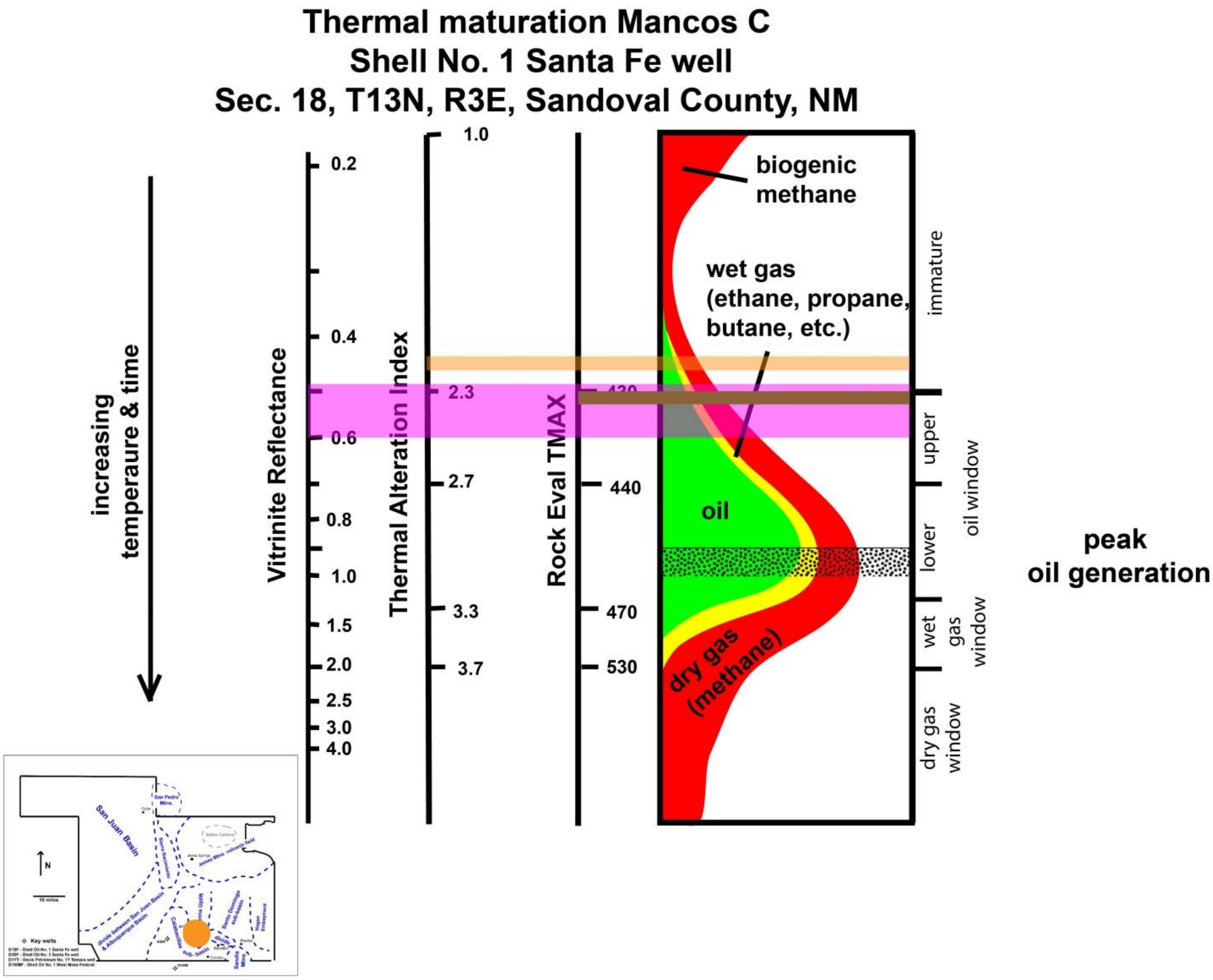

Figure S5. Petroleum generation profile for the Mancos C in the Shell No. 1 Santa Fe well, located in Sec. 18, T13N, R3E Sandoval County. Note that three maturation parameters (vitrinite reflectance, Thermal Alteration Index, Rock-Eval TMAX) determined on samples from this well indicate that the Mancos C is located in the uppermost part of the oil window or may even be thermally immature.

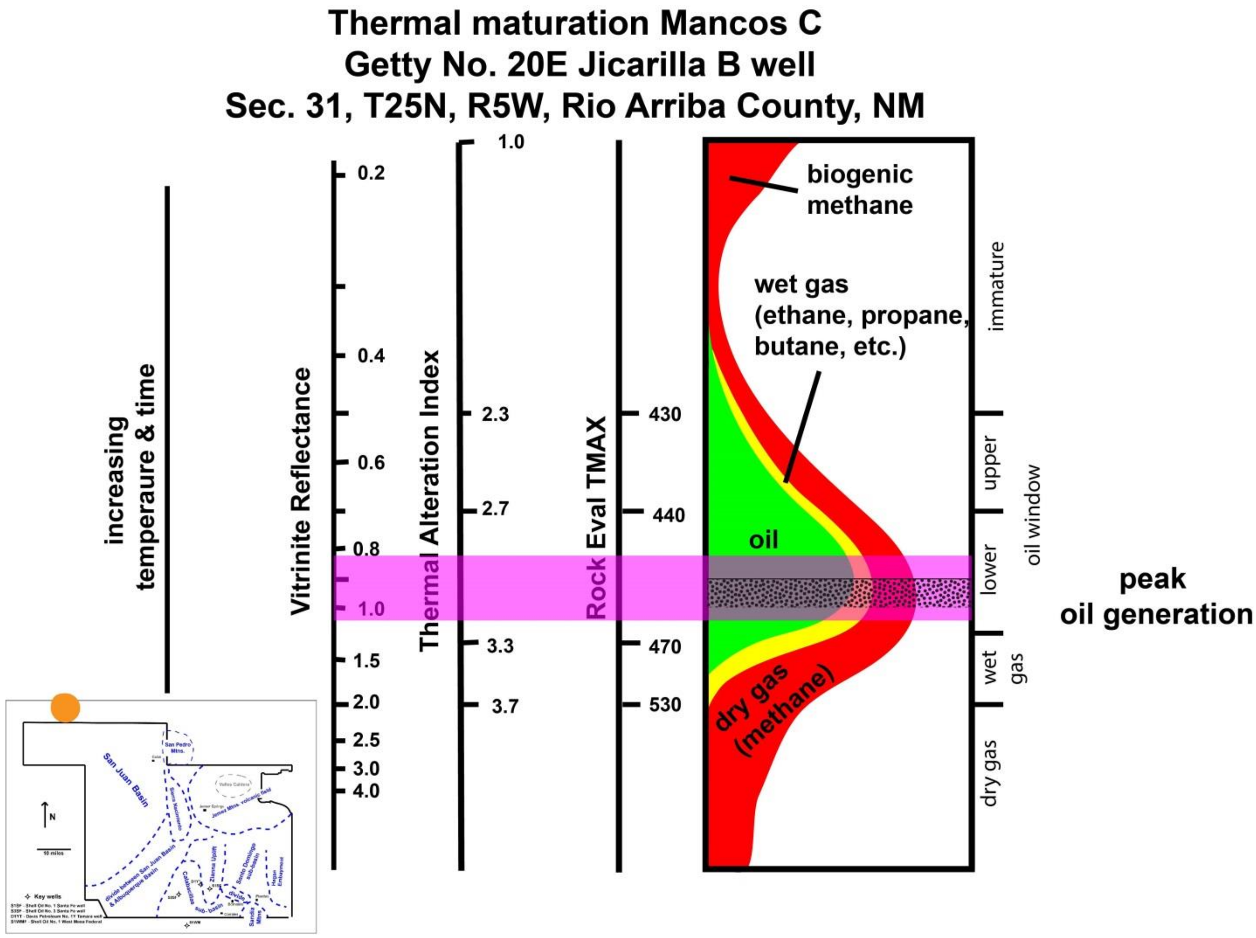

Figure S6. Petroleum generation profile for the Mancos C in the Getty No. 20E Jicarilla B well, located in Sec. 31, T25N, R5W, Rio Arriba County. Note that thermal maturation as determined by vitrinite reflectance places the Mancos C at peak oil generation.

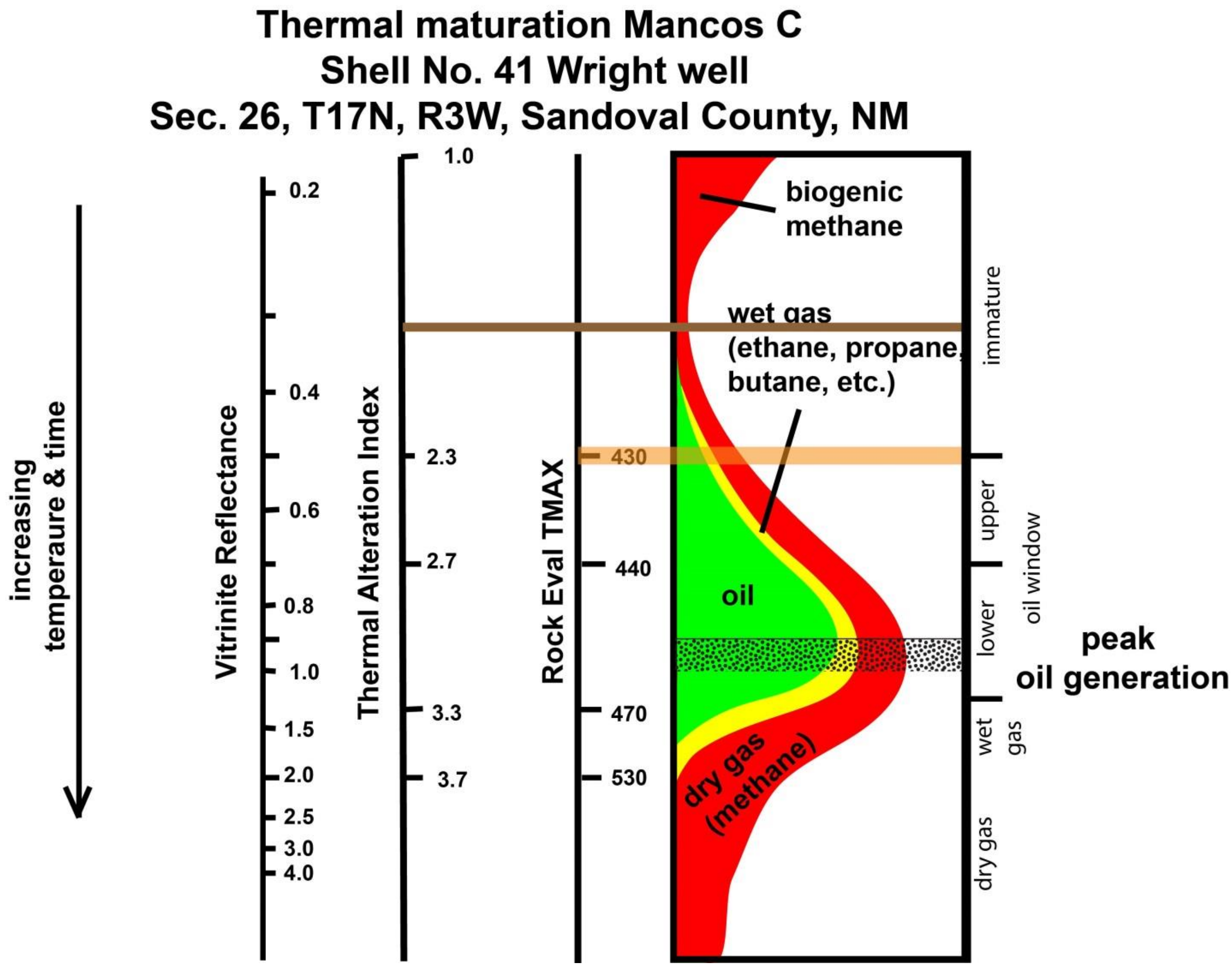

Figure S7. Petroleum generation profile for the Mancos C in the Shell No. 41 Wright well, located in Sec. 26, T17N, R3W, Sandoval County. Note that thermal maturation as determined by the Thermal Alteration Index and Rock-Eval TMAX places the Mancos C in the immature window where it has not generated oil.

Davis Petroleum No. 1Y Tamara
Sec. 3 - T13N - R2E

Stratigraphic unit		Depth to top (ft)	R_p Predicted vitrinite reflectance	Thermal maturity
Mancos C		6904	0.74	uppermost part of lower oil window
Lower Mancos Shale	Upper Carlile	7318	0.78	
	Juana Lopez	7726	0.82	
	Lower Carlile	7850	0.84	
	Greenhorn	8042	0.86	
	Graneros	8108	0.86	
Todilto		8484	0.90	lower oil window (peak oil)

Figure S8. Predicted vitrinite reflectance (R_p) in Davis Petroleum No. 1Y Tamara well, located in Sec. 3, T13N, R2E, Sandoval County. See Figure S1 for location of well.

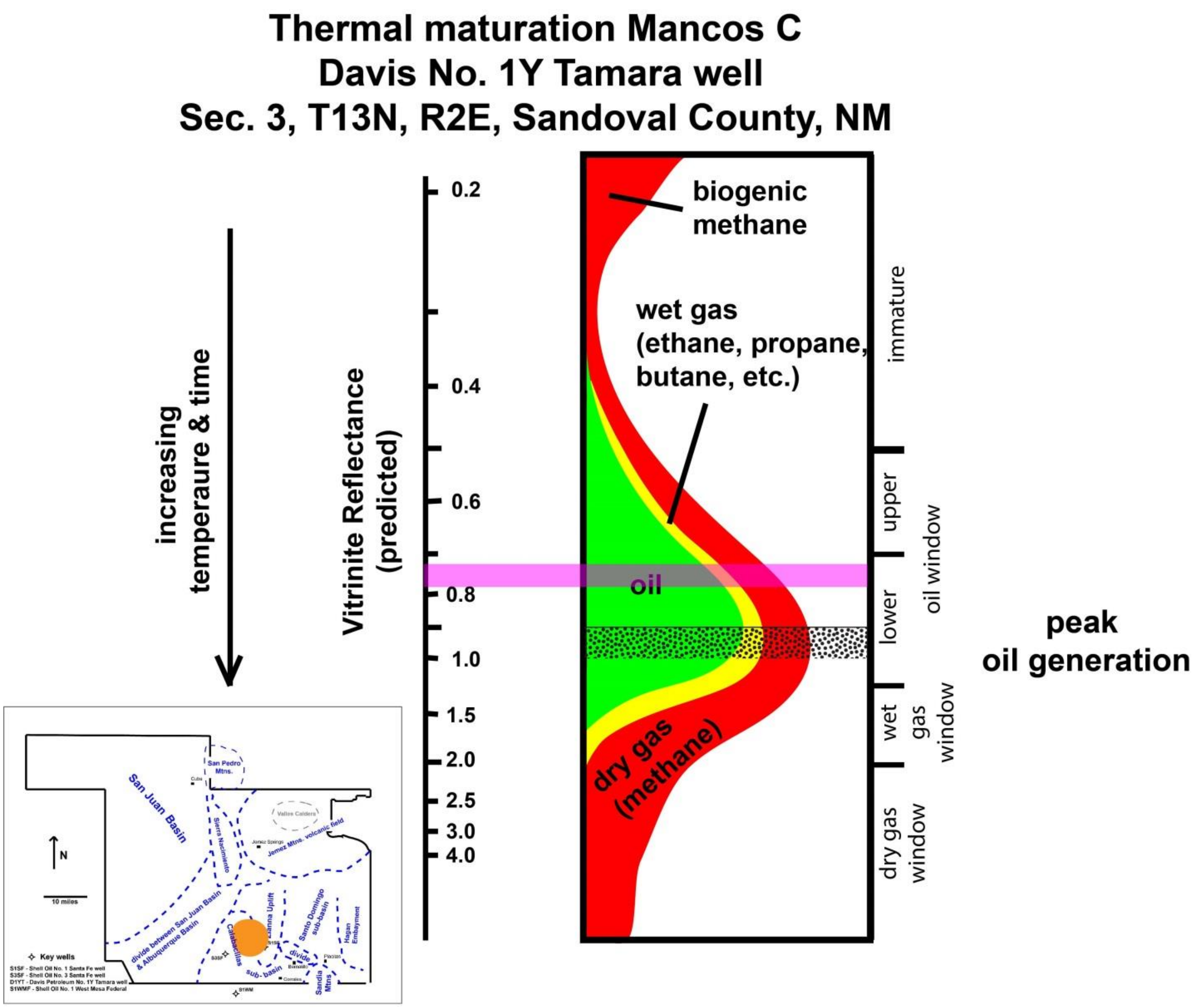

Figure S9. Petroleum generation profile for the Mancos C in the Davis Oil No. 1Y Tamara well, located in Sec. 3, T13N, R2E, Sandoval County. Predicted vitrinite reflectance places the Mancos C within the upper part of the lower oil window.

Shell Oil Co. No. 3 Santa Fe
Sec. 28 - T13N - R1E

Stratigraphic unit		Depth to top (ft)	R_p Predicted vitrinite reflectance	Thermal maturity
Lewis		4144	0.46	immature
Menefee		5196	0.57	upper oil window
Mancos A & B		6324	0.68	
Mancos C		7414	0.79	uppermost part of lower oil window
Lower Mancos Shale	Upper Carlile	7800	0.83	
	Juana Lopez	8212	0.87	
	Lower Carlile	8352	0.89	
	Greenhorn	8560	0.91	lower oil window (peak oil)
	Graneros	8638	0.92	
Todilto		10018	1.06	

Figure S10. Predicted vitrinite reflectance (R_p) in Shell Oil No. 3 Santa Fe well, located in Sec. 28, T13N, R1E, Sandoval County. See Figure S1 for location of well.

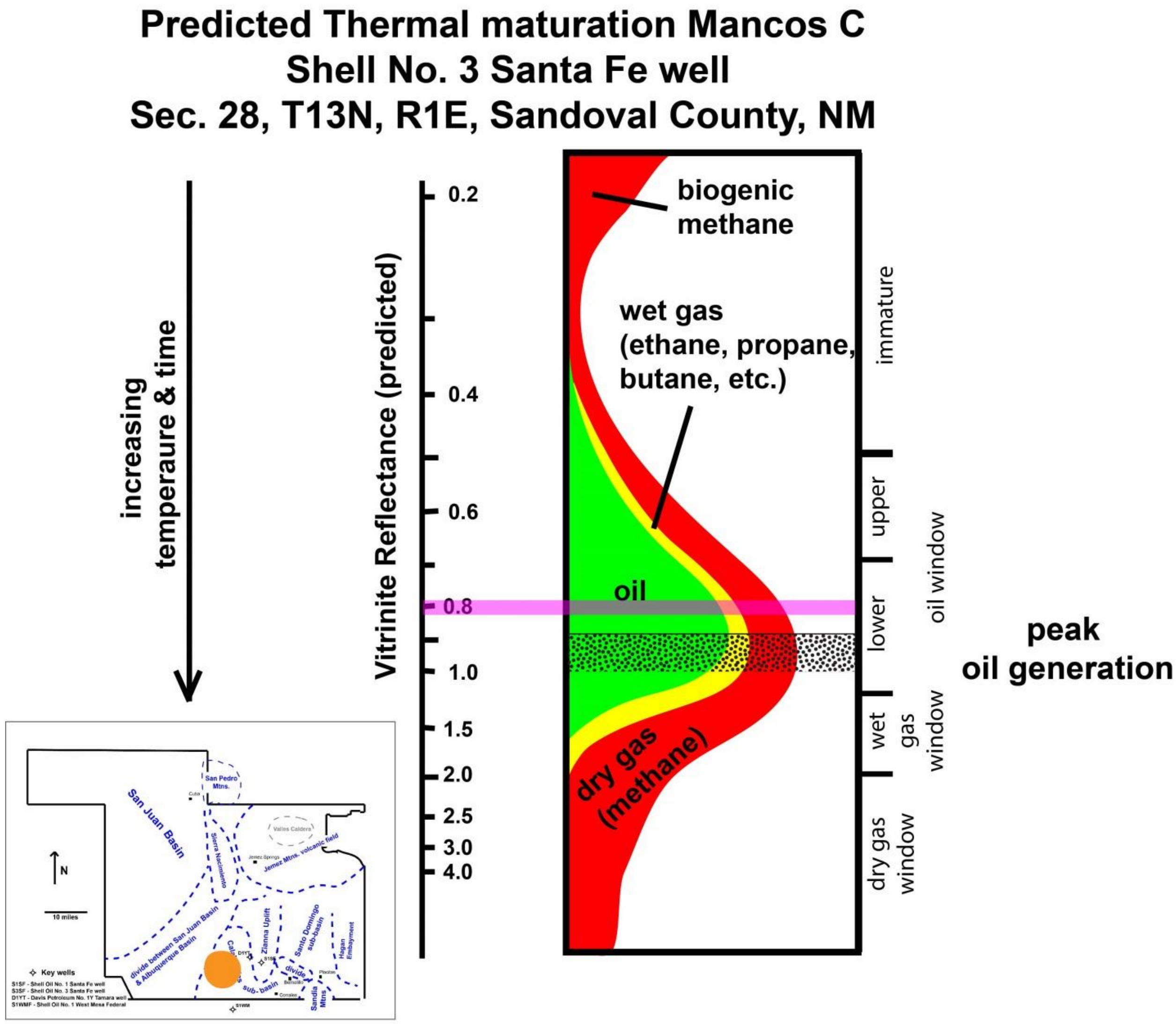

Figure S11. Petroleum generation profile for the Mancos C in the Shell No. 3 Santa Fe well, located in Sec. 28, T13N, R1E. Predicted vitrinite reflectance places the Mancos C in the upper part of the lower oil window, shy of peak oil generation.

The Calabacillas sub-basin of the Albuquerque Basin wraps around the southern end of the Zianna Uplift. To the west, an arm of the Calabacillas sub-basin occupies the area between the Zianna Uplift on the east and the western boundary of the Albuquerque Basin on the west. Essentially the sub-basin sits between the Davis No. 1Y Tamara well and the Shell No. 3 Santa Fe well. No direct depth data are available for this area because no exploratory wells have been drilled. In the original report on oil and gas potential of Sandoval County, Connell's (2008b) cross section A-A' was used to obtain an estimate of depths to various source rock units in the western arm of the Calabacillas sub-basin. Utilizing the thermal maturation model, the Mancos C as well as the source units in the Lower Mancos Shale were estimated to be in the upper oil window. This resulted in assignment of a low oil potential.

Subsequent communication with staff from Thrust Energy revealed that reflection seismic lines indicate that the Lower Mancos Shale lies at sufficient depth within the western arm of the Calabacillas sub-basin to have attained more optimal oil generation. However, due to the proprietary nature of the seismic data used by Thrust Energy, necessary seismic data could not be made available for this project.

In lieu of reflection seismic data, it was decided to utilize a published three-dimensional, gravity-derived model of Tertiary rift-fill thickness in the Albuquerque Basin (Grauch and Connell, 2013). That model indicates that rift-fill strata in the Calabacillas sub-basin between the Davis No. 1Y Tamara and the Shell No. 3 Santa Fe wells are 0.25 km (800 ft) thicker than in the No. 1 Santa Fe well over much of the area and as much as 0.5 km (1600 ft) thicker in the deepest area which lies just to the west of the Zianna Uplift. Thickness of the rift fill is correlative with the depth at which underlying Cretaceous source rocks lie within the Albuquerque Basin. Application of the depth-dependent thermal model places the Lower Mancos strata at peak oil generation and the Mancos C just shy of peak oil generation where it is 800 ft deeper (Figures S12, S13). In the eastern, deepest area the Mancos C and all of the source rocks in the Lower Mancos Shale are at peak oil generation with a predicted R_o for the Mancos C of 0.95. Therefore, this area should be considered to have moderate oil potential. Note that, as above, the absence of deep exploratory test wells precludes the possibility of testing significant flows of oil from any of the shale units and also the possibility of obtaining shows of oil or gas resulting in and therefore precludes assignment of a high oil potential. Oil production from the Mancos Shale in the San Juan Basin is obtained from thin sandstones that are interbedded with the shales (Broadhead, 2015). The Mancos C is the primary productive unit in the San Juan Basin. As described in the main report, the Lower Mancos Shale is also productive. It is unknown what the reservoir capability of these units is in the Albuquerque Basin compared to the reservoir capability in the Sandoval County part of the San Juan Basin. The limited data from the limited exploratory wells indicate that lithologies (rock types) are similar in both areas and therefore reservoir capabilities should be somewhat similar in both areas with the Mancos C regarded as the primary exploratory target and the Lower Mancos Shale regarded as the secondary exploration target.

To the north, the Calabacillas sub-basin becomes shallower. Three miles north of the Davis No. 1Y Tamara well the rift-fill thickness map of Grauch and Connell (2013) indicates that the Mancos C should be present at approximately the same depth that it is in the Shell No. 1 Santa Fe well. Therefore, the Mancos C and the underlying Lower Mancos strata have been matured to only the upper part of the oil window, rendering a low potential for oil in these shales. Even further to the north, the Mancos becomes shallower and therefore thermally immature and has very low potential.

To the south of the Zianna Uplift, the Calabacillas sub-basin of the Albuquerque Basin becomes deeper. In the Shell No. 1 West Mesa Federal well, located 3 ½ miles south of the Sandoval-Bernalillo county line, the top of the Mancos C is present at a depth of 25,980 ft. This is 20,560 ft deeper than in the Shell No. 1 Santa Fe well. The U.S. Geological Survey thermal model of the West Mesa Federal well (Johnson et al., 2001) placed the Mancos C and Lower Mancos strata in the thermogenic gas zone. Application of the thermal model developed for this project indicates that these strata will have been matured into the lower part of the wet gas window (Figures S14, S15). Therefore, any hydrocarbons that will be found will be methane gas along natural gas liquids (ethane, propane, butane).

To the east of the Zianna Uplift lies the divide between the Calabacillas sub-basin (of the Albuquerque Basin) and the Santo Domingo sub-basin (of the Española Basin). This divide is an east-west trending structurally high area. Application of the Grauch and Connell (2013) gravity model indicates that the Mancos C is present at a depth of approximately 10,400 ft on the divide at a location five miles east of the Shell No. 1 Santa Fe well. Application of the depth-dependent thermal model indicates that the entire Mancos Shale, including the Mancos C, has been matured to peak oil generation on the divide (Figures S16, S17). Therefore, the Mancos C and the entire Lower Mancos section are assigned a moderate oil potential. Again, a high potential is not assigned because no wells have drilled the Mancos, precluding the testing for flows of hydrocarbons or even obtaining shows while drilling through this section. Given that the Mancos

C is the primary productive Mancos unit in the San Juan Basin, it should be considered to have a higher potential than the underlying Lower Mancos strata.

Northward from the divide, strata dip into the Santo Domingo sub-basin. The gravity model of Grauch and Connell (2013) indicates that Cretaceous strata in this structurally low area are 8,200 ft deeper than in the Shell No. 1 Santa Fe well. Application of the depth-dependent thermal model places the Lewis Shale at peak oil generation. The entire Mancos Shale and the Jurassic Todilto limestones are within the thermogenic wet gas window (Figures S18, S19). The potential in these units is therefore gas. Although the Lewis is in the oil window, it should be noted that production within the Lewis in the San Juan Basin is gas and is obtained from the Chacra sandstones in the upper part of the Lewis. In the Shell No. 1 Santa Fe well, there is a visual determination of kerogen types on one sample of the Lewis Shale and Rock-Eval pyrolysis measurements on two samples of the Lewis (kerogen is the organic matter in the shales which, when heated over long periods of time, produces the oil and gas that is found in shales and other types of reservoir rocks). The visual determination of kerogen types indicates the kerogens are a mixture of oil-prone, gas-prone and nongenerative types. The Rock-Eval pyrolysis measurements indicate that the gas-prone and nongenerative types are dominant. This indicates that The Lewis will have generated gas rather than oil upon thermal maturation. Furthermore, the Chacra sandstones occur along a northwest-southeast trend that passes through northwestern Sandoval County. The available information indicates that the Chacra trend is located southwest of the Santo Domingo sub-basin. Although the Lewis is mature in the Santo Domingo sub-basin its potential should be considered low because the very few wells drilled in the area suggest that the Chacra reservoir facies is apparently not present in the sub-basin. The Lewis potential is for gas.

Calabacillas sub-basin
where strata 800 ft deeper than in Shell No. 1 Santa Fe well

Stratigraphic unit		Depth to top (ft)	R_p Predicted vitrinite reflectance	Thermal maturity
Lewis		4964	0.54	immature
Menefee		6016	0.65	upper oil window
Mancos A & B		7144	0.76	upper part of lower oil window
Mancos C		8234	0.88	
Lower Mancos Shale	Upper Carlile	8620	0.92	lower oil window (peak oil)
	Juana Lopez	9032	0.96	
	Lower Carlile	9172	0.97	
	Greenhorn	9380	0.99	
	Graneros	9458	1.00	
Todilto		10838	1.14	

Figure S12. Predicted vitrinite reflectance (R_p) in northwestern arm Calabacillas sub-basin where strata are 800 ft deeper than in the Shell No. 3 Santa Fe well. See Figure S1 for location of northwestern arm of the sub-basin.

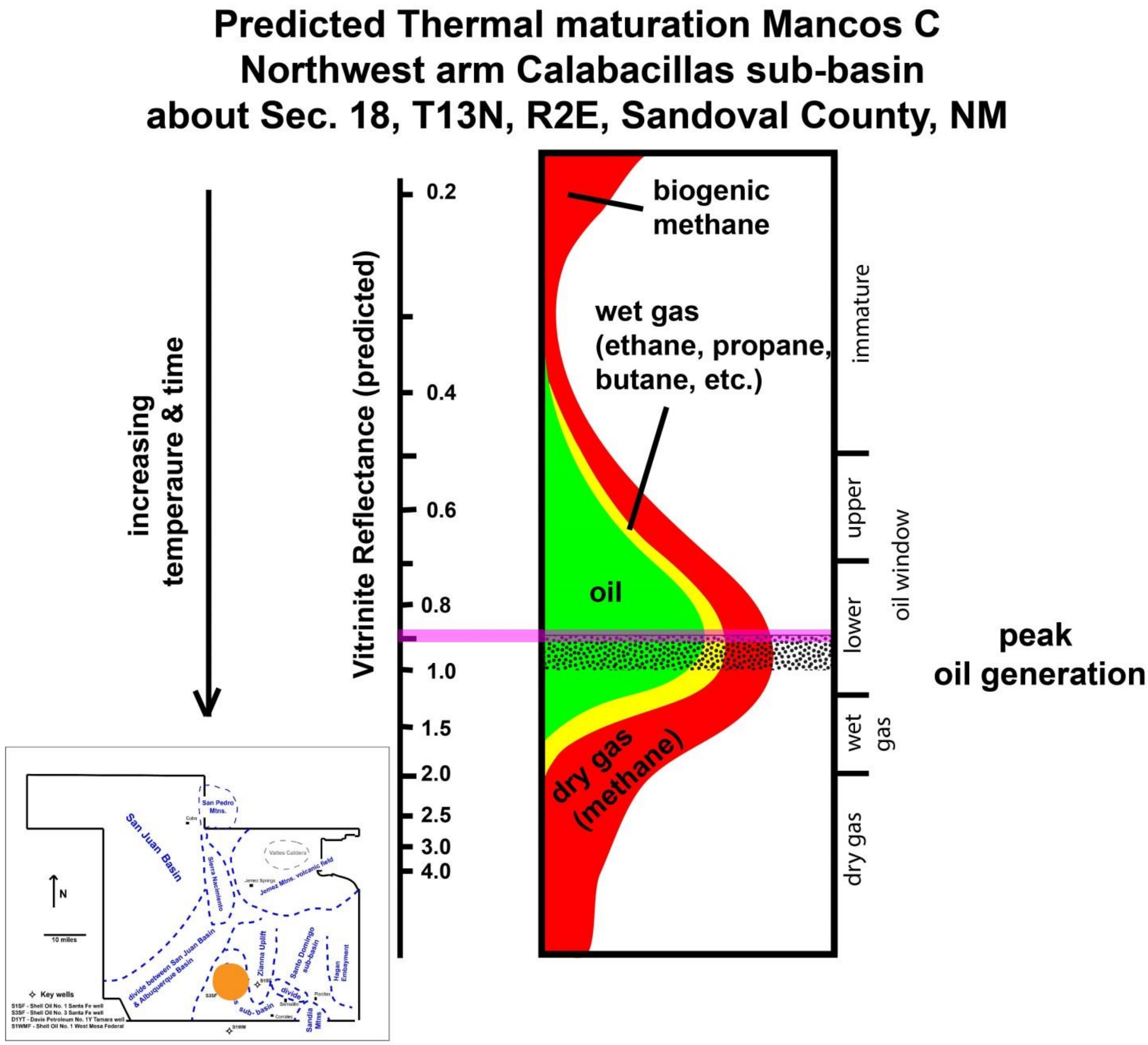

Figure S13. Petroleum generation profile for the Mancos C in the northwest arm of the Calabacillas sub-basin where the Mancos C is 800 ft deeper than in the Shell No. 3 Santa Fe well. Predicted vitrinite reflectance places the Mancos C at the onset of peak oil generation.

Shell Oil No. 1 West Mesa Federal
Sec. 24 - T11N - R1E

Stratigraphic unit		Depth to top (ft)	R_p Predicted vitrinite reflectance	Thermal maturity
Mancos A & B		16970	1.77	wet gas window
Mancos C		17780	1.85	
Lower Mancos Shale	Upper Carlile	18164	1.89	
	Juana Lopez	18490	1.92	
	Lower Carlile	18574	1.93	
	Greenhorn	18746	1.95	
	Graneros	18778	1.95	
Morrison		19136	1.99	
Todilto (projected)		20204	2.10*	dry gas window

Figure S14. Predicted vitrinite reflectance (R_p) in Shell Oil No. 1 West Mesa Federal well, located in Sec. 24, T11N, R1E, Bernalillo County. See Figure S1 for location of well.

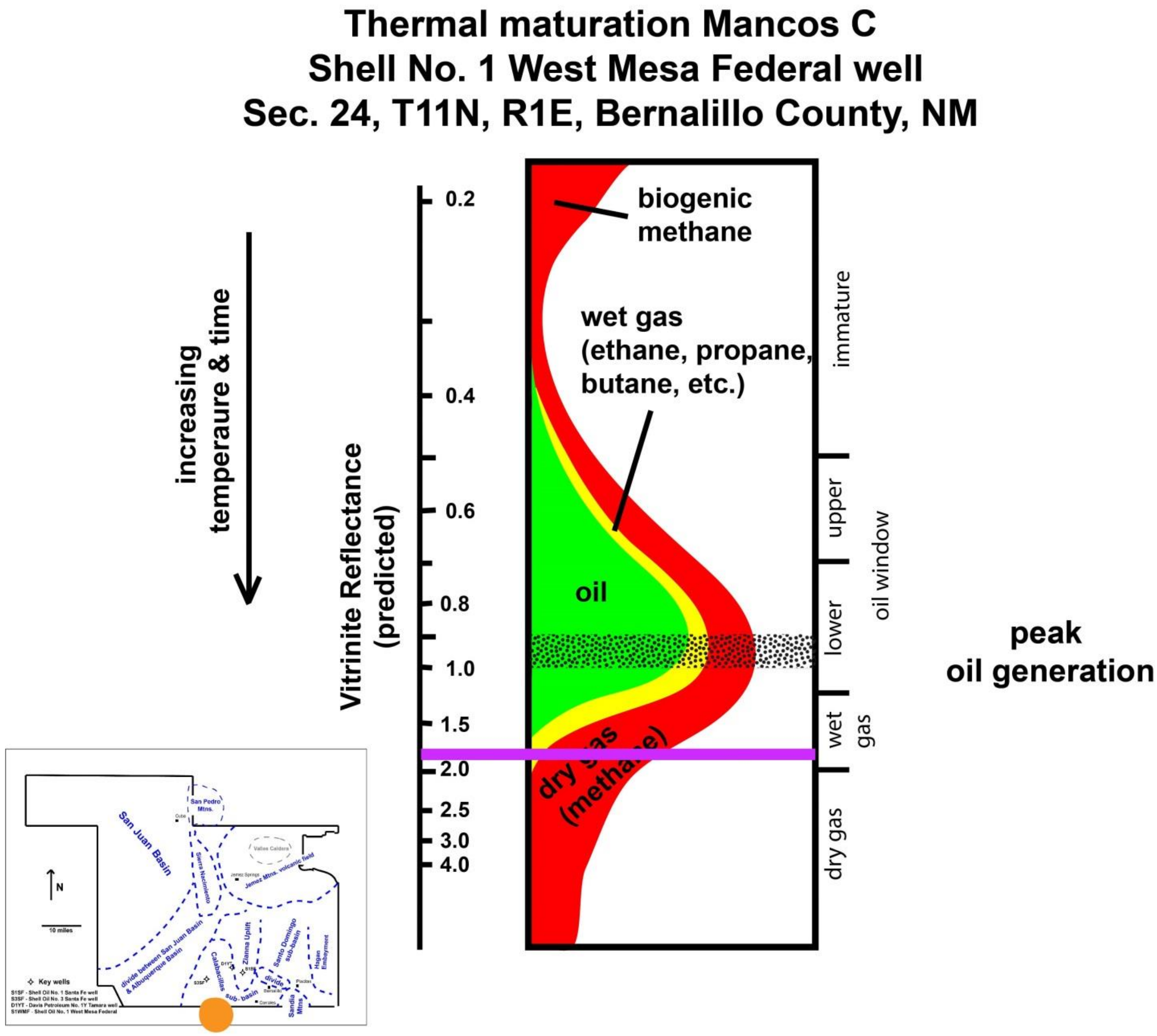

Figure S15. Petroleum generation profile for the Mancos C in the Shell No. 1 West Mesa Federal well, located in Sec. 24, T11N, R1E Bernalillo County. Predicted vitrinite reflectance places the Mancos C in the lowermost part of the wet gas window.

Calabacillas - Santo Domingo basin divide

Stratigraphic unit		Depth to top (ft)	R p Predicted vitrinite reflectance	Thermal maturity
Lewis		8064	0.86	upper part of lower oil window
Menefee		8516	0.90	lower oil window (peak oil)
Mancos A & B		9440	1.00	
Mancos C		10340	1.09	
Lower Mancos Shale	Upper Carlile	10618	1.12	
	Juana Lopez	11014	1.16	
	Lower Carlile	11158	1.17	
	Greenhorn	11346	1.19	
	Graneros	11412	1.20	
Todilto		12370	1.30	lower oil window

Figure S16. Predicted vitrinite reflectance (R_p) on the divide between the Calabacillas and Santo Domingo sub-basins where Cretaceous strata are estimated to be 4920 ft deeper than in the Shell No. 1 West Mesa Federal well. See Figure S1 for location of the divide.

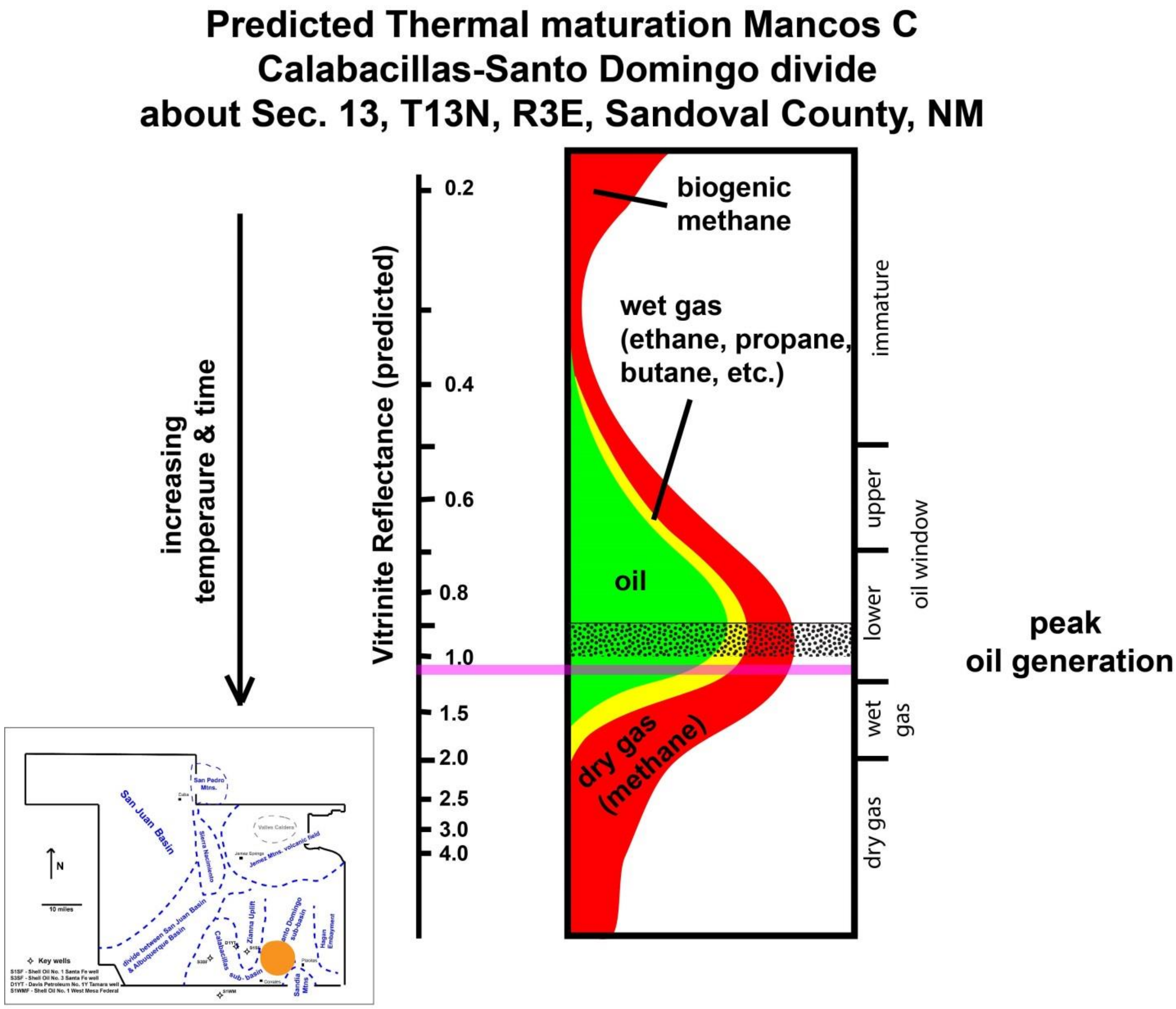

Figure S17. Petroleum generation profile for the Mancos C on the divide between the Calabacillas sub-basin of the Albuquerque Basin and the Santo Domingo sub-basin of the Espanola Basin. Approximate location of the profile is Sec. 13, T13N, R3E Sandoval County. Predicted vitrinite reflectance places the Mancos C in the lowermost part of the oil window below peak oil generation.

Southern Santo Domingo sub-basin

Stratigraphic unit		Depth to top (ft)	R_p Predicted vitrinite reflectance	Thermal maturity
Lewis		11344	1.19	lower oil window (peak oil)
Menefee		11796	1.24	lower oil window
Mancos A & B		12720	1.33	wet gas window
Mancos C		13620	1.43	
Lower Mancos Shale	Upper Carlile	13898	1.45	
	Juana Lopez	14294	1.49	
	Lower Carlile	14438	1.51	
	Greenhorn	14626	1.53	
	Graneros	14692	1.53	
Todilto		15650	1.63	

Figure S18. Predicted vitrinite reflectance (R_p) in the southern part of the Santo Domingo sub-basin where strata are estimated to be 8200 ft deeper than in the Shell No. 1 Santa Fe well. See Figure S1 for location of the Santo Domingo sub-basin.

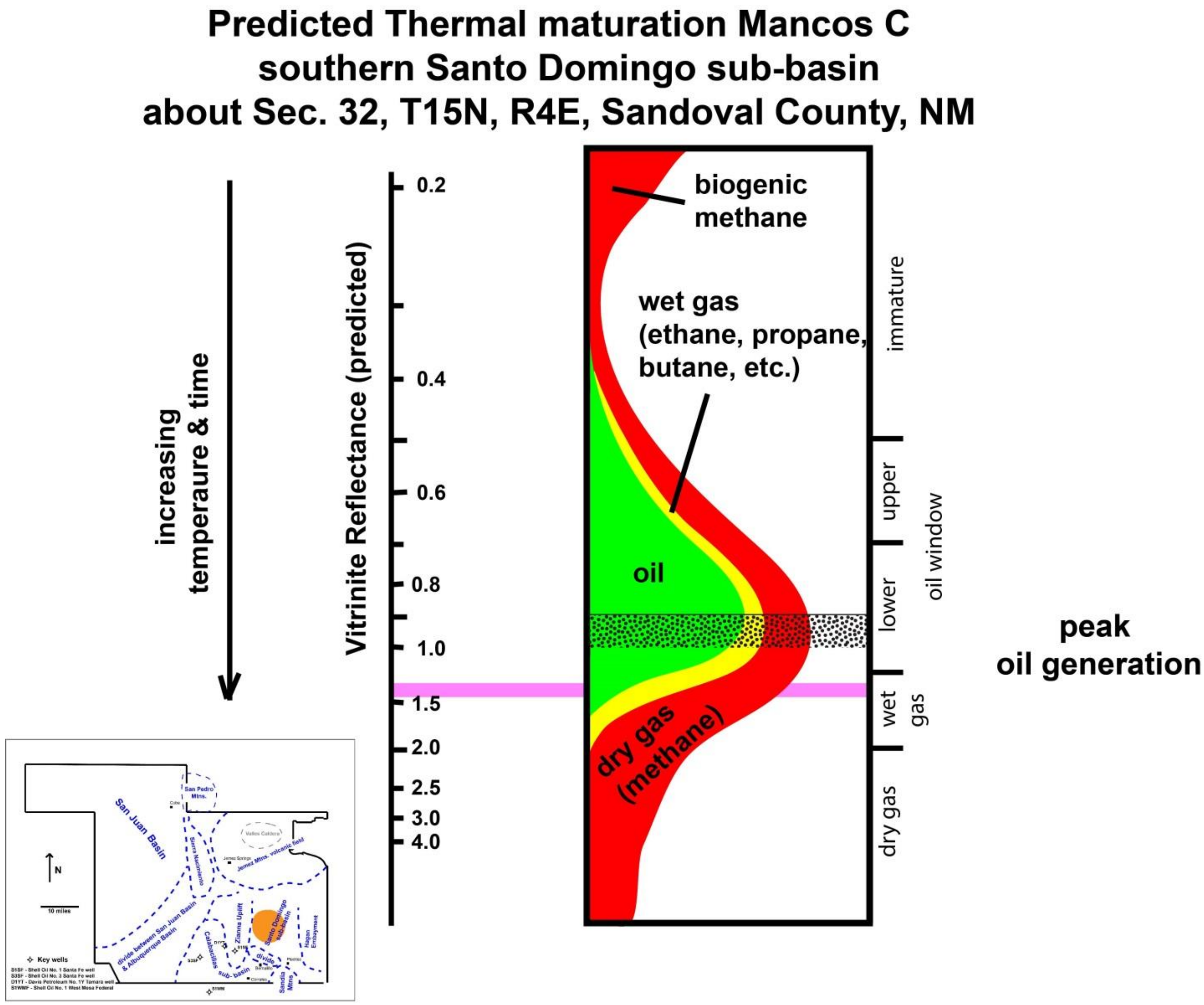

Figure S19. Petroleum generation profile for the Mancos C in the southern part of the Santo Domingo sub-basin of the Espanola Basin. Approximate location of the profile is in Sec. 32, T15N, R4E Sandoval County. Predicted vitrinite reflectance places the Mancos C within the wet gas window.

Summary of Petroleum Potential in Albuquerque Basin Part of Sandoval County

Thermal maturity of the Mancos C, the Lower Mancos Shale, and the Todilto limestones is summarized in Figures S20, S21, and S22. These distributions of maturity exert the primary control on oil and gas potential in the Mancos shales because the low permeability in the shale units restricts the ability of generated hydrocarbons to migrate (move) significant lateral distances within the rock. The hydrocarbons are found close to where they were generated. Maximum oil potential within the Mancos C and the Lower Mancos Shale will be located where these shales have been matured to the stage of peak oil generation (vitrinite reflectance values ranging from 0.9 to 1.0). The Mancos C should be considered as the main exploratory target because it is the primary productive Mancos stratigraphic unit in the San Juan Basin portion of Sandoval County. The various stratigraphic units of the Lower Mancos Shale provide ancillary production in the San Juan Basin.

In the Sandoval County part of the Calabacillas sub-basin, the maximum oil potential occurs along a trend 5 to 6 miles wide located between the Davis No. 1Y Tamara well and the Shell No. 3 Santa Fe well. The Lower Mancos is at peak oil generation in the Calabacillas sub-basin between the Davis No. 1Y Tamara well and the Shell No. 3 Santa Fe well. The overlying Mancos C, which is the primary productive Mancos unit in the San Juan Basin, is within the lower oil window but is not sufficiently mature to have attained peak oil generation except in the deepest areas so that its potential is somewhat limited. Potential for oil production in this area is moderate and cannot be considered high because of an absence of wells in the sub-basin so that no shows, which would support a high potential, and no flow tests of hydrocarbons, which would support a high potential, have been obtained. Flow tests conducted before or after stimulation of the reservoir indicate the productive capability of the shale reservoir and are necessary for the assignment of a high oil or natural gas potential. Oil potential in the area would be somewhat higher if the Mancos C had been matured to peak oil generation.

Further north within the Calabacillas sub-basin oil potential decreases as strata become shallower and less mature. Along the axis of the sub-basin three miles north of the Davis No. 1Y Tamara well, strata are at the same depth as in the Shell No. 1 Santa Fe well and will have a correspondingly low oil potential. Yet even further north strata are shallower and potential is very low.

To the west in the Shell No. 3 Santa Fe, only the lower part of the Lower Mancos Shale has been matured to peak oil generation. Oil potential is still moderate but is less than along the axis of the Calabacillas sub-basin because only a smaller part of the section has attained peak oil generation. To the east on the Zianna Uplift where the Shell No. 1 Santa Fe was drilled, both the Mancos C and the Lower Mancos are within the upper oil window and oil potential is low.

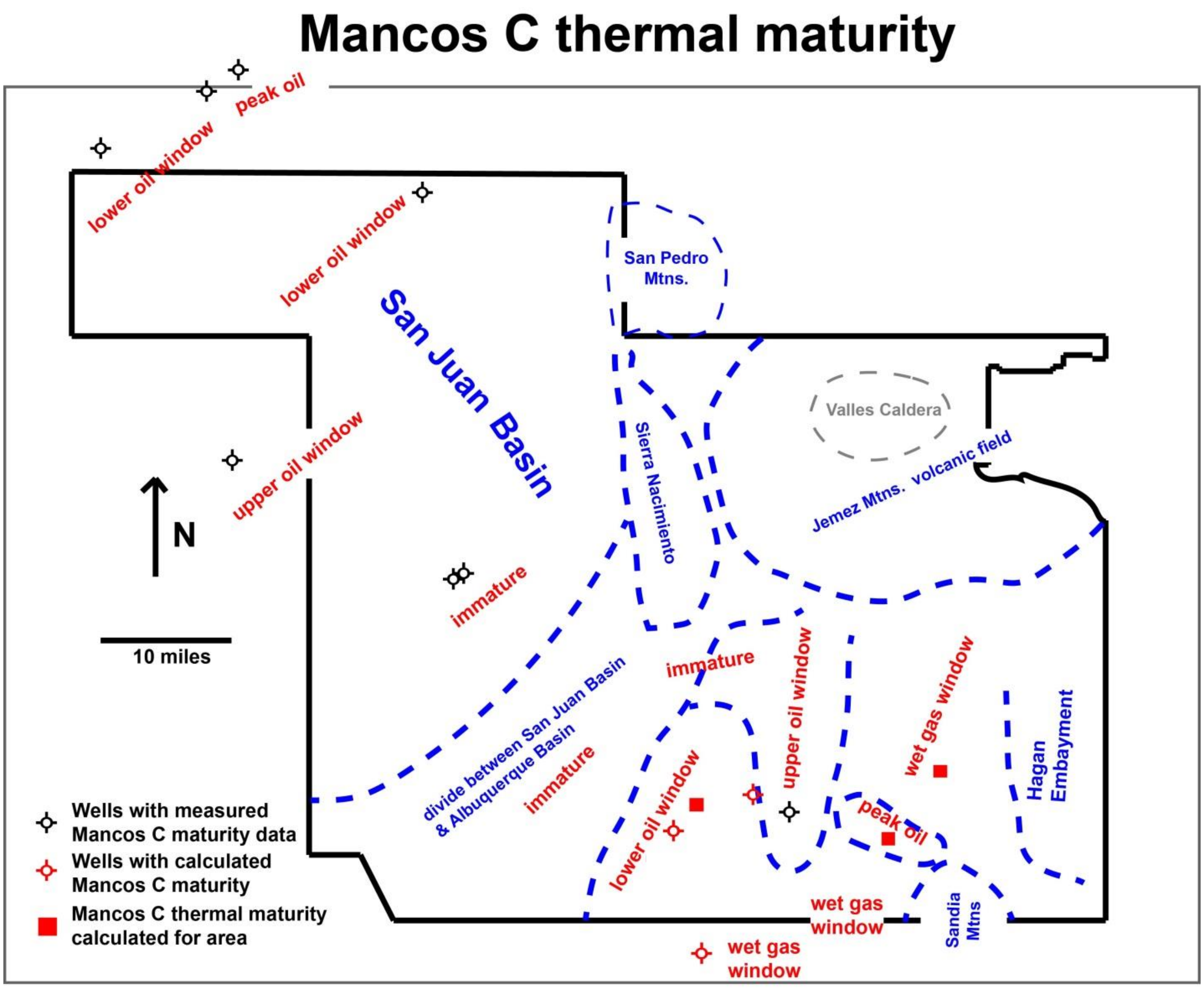

Figure S20. Thermal maturity of the Mancos C in Sandoval County.

To the south, the Calabacillas sub-basin becomes very deep in Bernalillo County. In this area, high temperatures acting over geologic time have been too high for oil preservation. Potential is for gas with gas liquids and is moderate. In the Shell No. 1 West Mesa Federal well which was drilled in the wet gas window, attempts were made to complete this vertical well in the Point Lookout Sandstone, the Hosta sandstone, the lower Carlile shale, the Juana Lopez Member and the Graneros Shale-Dakota Sandstone interval but the resulting gas flows were insufficient to establish commercially viable volumes of production. It is unknown if commercially viable volumes of production could be established by a modern completion in any one of these reservoir zones utilizing an extended-reach horizontal well with accompanying multi-stage hydraulic fracturing.

The net effect of the preceding discussion is that there is an oil exploration fairway of moderate potential in the Mancos C and Lower Mancos Shale within the Calabacillas sub-basin. The fairway is approximately 5 to 6 miles wide and is situated between the Davis No. 1Y Tamara well and Shell No. 3 Santa Fe well. It extends north for a distance of approximately 3 miles north of the Davis Tamara well and south for a distance of approximately 7 miles south of the Davis Tamara well. The primary exploratory target is the Mancos C at a depth of approximately 8200 ft.

The divide between the Calabacillas sub-basin and the Santo Domingo sub-basin lies to the east of the Zianna Uplift. On the divide, both the Mancos C and the Lower Mancos Shale are predicted to have been matured to peak oil generation (Figures S8, S18). Potential is for oil and is moderate, and similar to areas described above is limited by an absence of exploratory wells that may confirm the presence of hydrocarbons through shows and may confirm the producibility of reservoir capability through flow tests.

Northward from the divide, strata dip into the Santo Domingo sub-basin. There, the Mancos C and the Lower Mancos Shale are in the wet gas window (Figures S18, S19). Potential is moderate and is for gas with natural gas liquids. Although the shallower Lewis Shale is within the oil window, the organic matter within the Lewis appears to consist of gas-prone types that would have generated gas rather than oil upon maturation. Furthermore the main Lewis reservoirs (Chacra sands) appear to be absent so that potential in the Lewis is low.

As strata dip under the Jemez Mountains volcanic field farther north , oil and gas potential is low. In the western part of this area, Cretaceous and Jurassic strata are absent. There are no petroleum source rocks present in the pre-Jurassic section so that oil and gas potential is low. Further to the east where Jurassic and Cretaceous strata are present, the intense heat associated with Tertiary and Quaternary volcanic activity and accompanying pervasive magmatic intrusion would have acted to naturally crack any reservoired oil into natural gas. Any potential is therefore for gas and not for oil. Furthermore, the rising magmas would have exsolved volcanic gases, which consist primarily of water and carbon dioxide (CO_2). The carbon dioxide, once exsolved from the magmas, enters the reservoirs and dilutes any hydrocarbon gases that may be present. The result is a low-quality gas with decreased energy content which is undesirable to produce. Gas potential is very low.

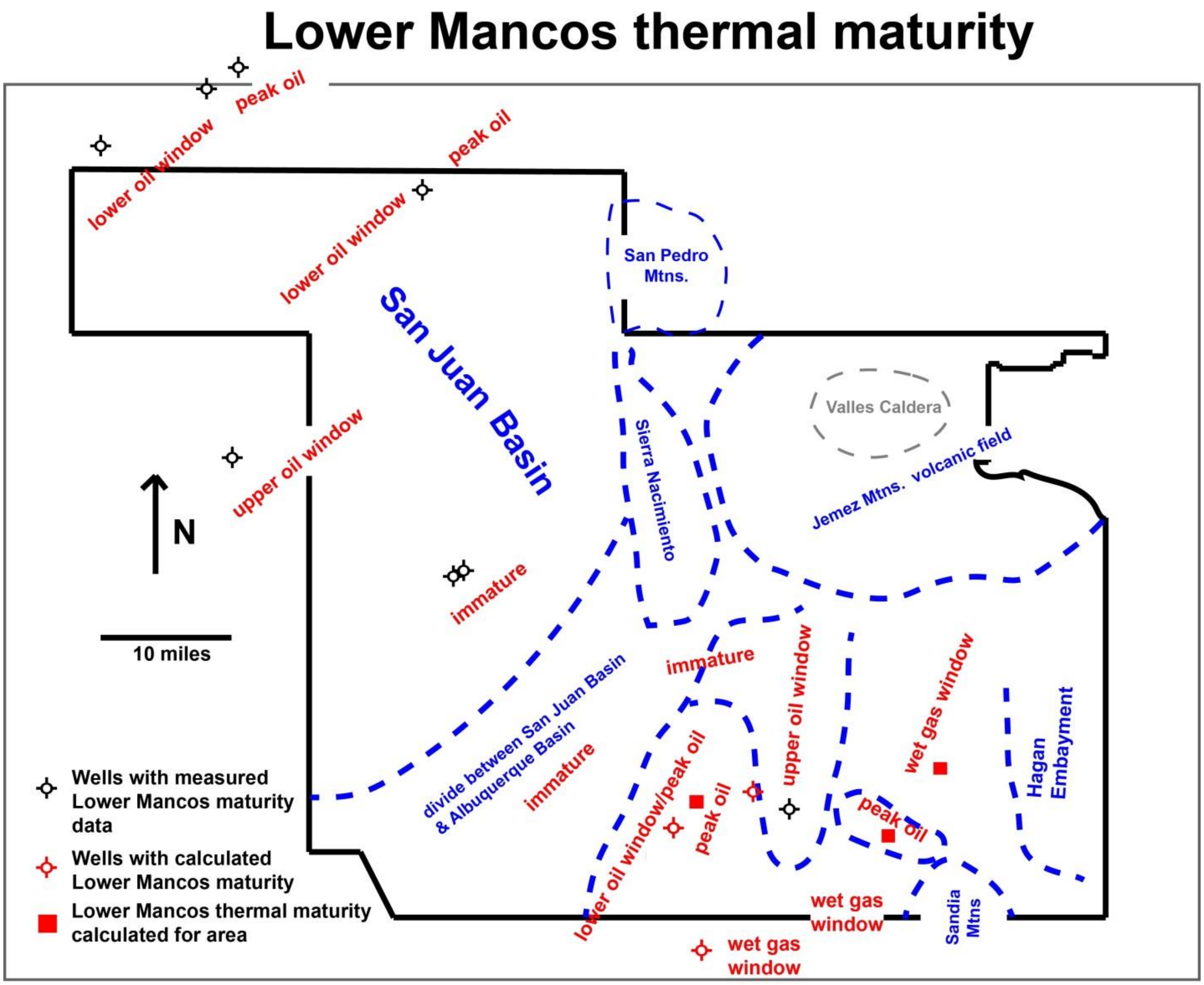

Figure S21. Thermal maturity of the Lower Mancos Shale in Sandoval County.

Todilto thermal maturity

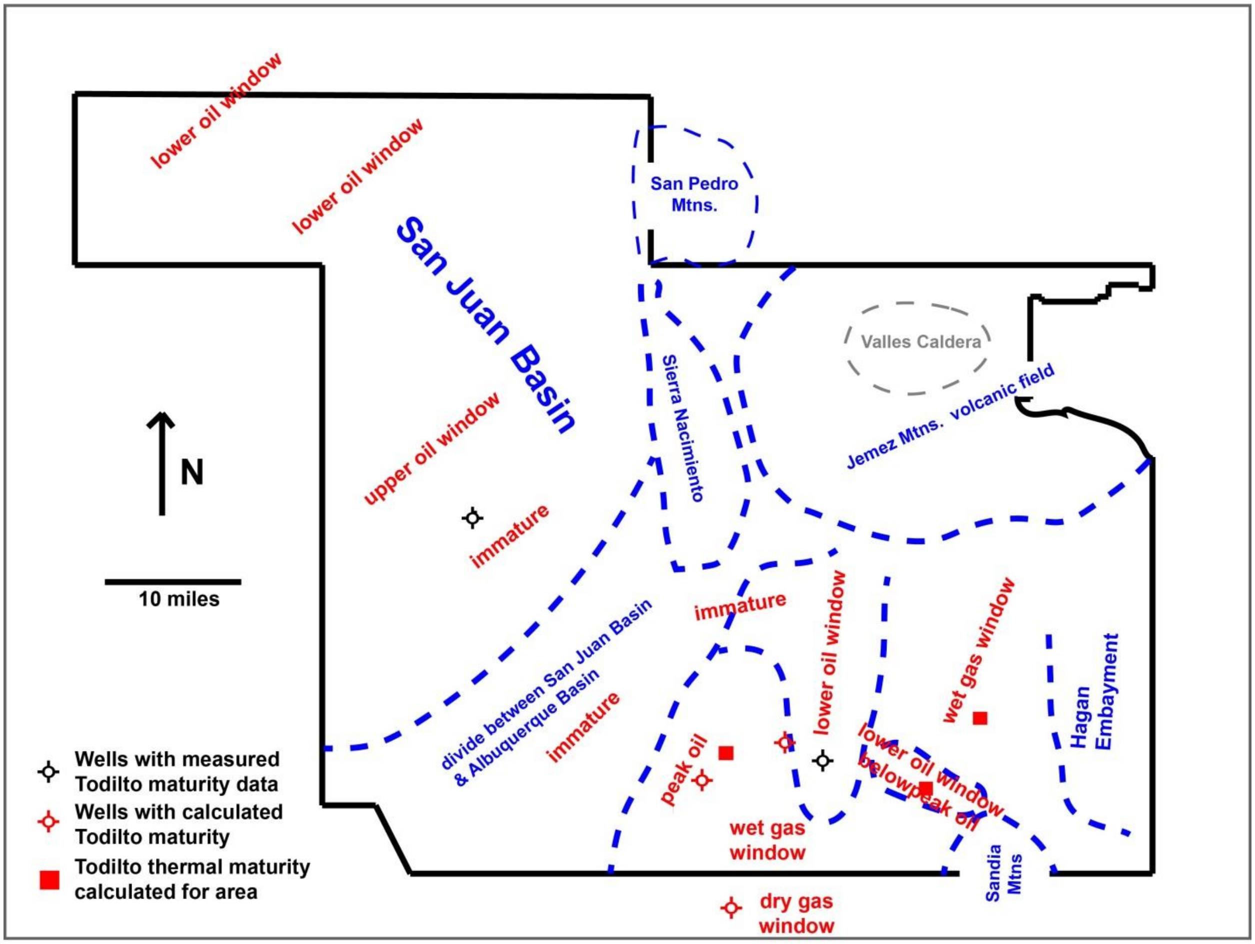

Figure S22. Thermal maturity of the Todilto limestones in Sandoval County.

The Todilto limestones and the underlying Entrada Sandstone form a couplet as far as petroleum exploration is concerned. The Todilto limestones contain substantial amounts of kerogen (organic matter) that, when heated through burial, form oil which is expelled into the underlying Entrada Sandstone. Unlike the thin sandstone beds in the Mancos shales, the Entrada is a widespread and very porous and permeable rock layer through which oil can readily migrate (or move). The oil will move upwards until it encounters a trap in the Entrada which blocks further movement. As noted in the main report on the petroleum potential of Sandoval County, Entrada traps in the San Juan Basin are small and are formed by relict sand dunes that are preserved on the upper surface of the Entrada. Typical Entrada oil accumulations will be produced by less than 5 vertically drilled wells that are drilled on 40-acre spacing (1/16 mi^2 per well) so that the typical Entrada oil field occupies less than ¼ mi^2. Because of the high permeability and far-reaching lateral extent of the Entrada, the oil may be trapped great distances from where it was generated. Areas associated with thermally immature Todilto limestones may trap oil or gas that was generated a considerable distance away. After the generated hydrocarbons enter the Entrada it migrates updip (essentially upslope) until it encounters a trap.

Prospecting for relict sand dune traps in the Entrada in a structurally complex area such as the Albuquerque Basin will be difficult and inefficient without the acquisition of extensive 3D seismic surveys. 3D seismic surveys will aid in pre-drill imaging of sand-dune traps but are expensive and time-consuming to acquire. Given the small size of Entrada oil accumulations that have already been discovered in the San Juan Basin and the expense associated with 3D seismic surveys, exploration for similar features in the Albuquerque Basin may be non-commercial. Exploration for larger traps associated with rift structures may be more cost effective.

The large structures found in rift settings such as the Albuquerque basin lend themselves to large traps that contain large reserves of oil or gas. Accumulations would be gas in the deeper, more mature areas and oil or migrated gas in the shallower less mature areas (Figure S20). Potential for oil and gas in the Entrada is tempered because the exploratory wells drilled in the Sandoval County part of the Albuquerque Basin do not have reported shows of oil or gas in the Entrada despite having been drilled on the tops or flanks of structures. The Shell No. 1 Santa Fe, drilled on the Zianna Uplift, ran a drill-stem test through the Entrada and recovered mud-cut water with no oil. The absence of oil recovery by the drill-stem test is a negative factor when considering oil and gas potential. Therefore, although the Todilto is a thermally mature source rock within the Sandoval County part of the Albuquerque Basin, the potential for oil and gas is considered to be low.

The portion of the Hagan embayment that extends into Sandoval County appears to have a low potential for oil and gas. Strata in this down folded, synclinal structural feature dip east and northeast into the subsurface of the Espanola Basin from their outcrops on the eastern flank of the Sandia Mountains. Black (1999) provided an excellent summary of the subsurface geology and exploratory drilling efforts in the Sandoval County part of the embayment. Apart from an early well drilled in 1954, there were 11 wells drilled from 1976 through 1994 in four exploratory phases. Several of the wells encountered substantive oil shows (see Black, 1999). Most of the oil shows were in the Dakota Sandstone, but there were also shows in the Mancos Shale and in the Entrada Sandstone. Black concluded that a sizeable oil accumulation of more than 20 million bbls existed in the Dakota in Sections 18 and 19, T13N, R6E at one time but that the trap had been breached by erosion in relatively recent geological time. As a result of the breach, most of the oil leaked out. The oil shows encountered by the exploratory wells represent residual oil that remained in the reservoir. Although any trap in the deeper Entrada Sandstone does not appear to have been breached, oil shows in the Entrada are minor. To the southeast in Section 35, T13N, R6E, four of the exploratory wells drilled in the embayment encountered live oil shows in an apparent major fault zone that cut Cretaceous and Jurassic strata (Black, 1999). Apparently the fault zone acted as a conduit for leakage of oil to the subsurface. It appears that the integrity of traps in the Sandoval County part of the Hagan embayment has been compromised by Tertiary-aged structural movement and by Quaternary-aged erosion. Producible oil has naturally migrated to the surface. Therefore, oil and gas potential is low.

ASSESSMENT OF POSSIBLE GROUNDWATER CONTAMINATION FROM UNCONVENTIONAL OIL AND GAS DEVELOPMENT

Susceptibility and risk thresholds

Susceptibility

Susceptibility estimates the proclivity of a hazard occurring in a location, but does not include estimates of the frequency of the hazard occurring nor does it account for the costs of that hazard occurring. Since the beginning of the extensive use of horizontal drilling and hydraulic fracturing to develop unconventional shale reservoirs about ten years ago, concerns over groundwater contamination has driven the study of when, or if groundwater contamination occurs during unconventional oil and gas operations. These studies have been integrated into a large report by the U.S. Environmental Protection Agency (EPA, 2016). The USEPA report found that incidents of groundwater contamination could be directly linked to unconventional oil and gas operations, though in the western U.S. the number of incidents were few. There is a chance of groundwater contamination during various phases of oil and gas operations.

Susceptibility to upward-flowing (aquifer) contamination

There are two ways that groundwater contamination can occur: from upward or lateral flow in the below the surface; or downward flow from the surface. Subsurface contamination pathways include upward contamination flow from the target oil/gas reservoir through the overlying sealing formation (or caprock) via faults and fractures or by direct flow, and upward or lateral flow via leaky well bores. The primary causal factor of upward flow is pressurization, either of the reservoir over the long-term after active oil and gas operations, or during hydraulic fracturing of the reservoir in the short-term. Lateral subsurface contamination may also occur due to leakage from well bores directly into drinking water supplies in the portion of the well that penetrates through the aquifer. In most cases, documented subsurface contamination has been in the form of stray gas (EPA, 2016), with some cases of possible brine contamination in locations where the reservoir abuts the aquifer (Lange et al., 2013). Surface contamination is primarily via downward migration of produced fluids (brine or hydrocarbons) or other operational fluids into the aquifer. This occurs because of spills either at the wellhead or during transport. This pathway is generally considered to be the more likely of the two (EPA, 2016).

To assess the susceptibilities across Sandoval County for all of these hazards, specific thresholds are needed to assess the different pathways. For the subsurface contamination, or upward and lateral pathways, thresholds were developed based on Davies et al. (2012), Lange et al. (2013), Kissinger et al., (2013), and Westwood et al. (2017). The thresholds for low, moderate and high susceptibility for the different pathways are summarized in Table S1. In all cases, these are essentially stand-off distances: either a horizontal distance from the oil and gas well or a vertical separation between the reservoir and aquifer.

In addition to the hazard from leaky boreholes during operations, there is also a long-term hazard of groundwater contamination from upward flow of hydrocarbons along oil and gas wells through their casing, either active wells or abandoned wells.

Consider the upward flow from the reservoir to the aquifer. This can happen either quickly and primarily during the hydraulic fracturing of the reservoir (months to a year), or over a longer period due to a combination of an overpressured reservoir and the creation of a leakage path during oil and gas field operations (EPA, 2016). An overpressured reservoir is one which has a pressure gradient (psi/ft) greater than that caused by a column of water (i.e., hydrostatic pressure). Possible pathways include leakage directly upward through the overlying reservoir seal, upward along existing operating or abandoned boreholes, and upward along faults and fractures (EPA, 2016). The susceptibility of risk either due to short-term leakage during operations or from long-term leakage due to the disturbance of reservoir seals during operations is a function of vertical separation of the aquifer and the reservoir, the thickness of seals or confining layers between the reservoir and the aquifer, and the permeability of faults and fractures penetrating both the seals and the reservoir.

The basis of horizontal and vertical separations of well completions from aquifers and reservoirs has largely been based on the measured distances of fracture propagation in a series of papers summarized in Davies et al. (2014); in addition, the modeling incorporates studies of Lange et al. (2013), Kissinger et al. (2013) and Westwood et al. (2017), which are consistent with the field studies summarized in Davies et al. (2014). Table S1 summarizes these criteria.

For an unconventional or hybrid play to generate enough oil and gas to be profitable, the formation must be fractured to enhance the permeability. Without these fractures, fluid flow even under high pressure gradients is very slow. However, there are physical limitations on the distance fractures may propagate: it requires increasing amounts of energy and fluid to fracture further and further from the wellbore, both of which are limited by pump capacity and available water resources (Yew and Weng, 2015). If a leakage pathway or aquifer is further than the fractures can propagate, there is little chance of fluid migration into the aquifer.

With that said, during unconventional oil and gas operations more water is injected during hydraulic fracturing than is initially pumped out (Lange et al., 2013). This opens the possibility of over-pressurizing the reservoir, which may propagate through the reservoirs seal, driving brines and natural gas upward and outward into neighboring formations (Lange et al., 2013; EPA, 2016). If these formations hold aquifers, this could lead to unintentional contamination (EPA, 2016). These pathways are poorly understood in the scientific literature, but are a possibility. If an oil and gas reservoir that will be horizontally drilled and hydraulically fractured is immediately underlying an aquifer, then there is a high susceptibility to upward contamination especially over the long term (EPA, 2016). If there is more than one sealing formation between the reservoir and the aquifer, then the susceptibility is low.

Outward, lateral leakage from an oil and gas well into the aquifer depends on the integrity of well casing, which is made of multiple layers of concrete and steel that isolates the oil and gas well from the aquifer. Because of issues with groundwater contamination from vertical, conventional wells, improvements have been made to how and when these casings are put into place (Vidic et al., 2013; Brownlow et al., 2016; EPA, 2016). These well casings are required to be pressure, or bond tested, to ensure a good seal between the well bore and the surrounding aquifer (OCD, 2008). However, well casings are continually exposed to an acidic environment where oil and gas is flowing upward, and to an often oxidizing and corrosive environment externally where the casing is in contact with the aquifer. Over the long-term (decades), this may cause leakage from the oil and gas wellbore into the aquifer. Without monitoring, it is uncertain how long the contamination event will go on before detection.

If a well bore leaks into an aquifer, then hydrocarbons, particularly methane (stray gas), may migrate into existing water supply wells. Because most water wells create a cone of depression around them as they are pumped, where groundwater flows into the well from the regional aquifer, contaminants can also be drawn into water wells. The likelihood of a leaking oil and gas well contaminating a pumping water well would be accelerated, as compared to the natural movement of regional, slow groundwater. The contaminant transport preferentially goes into the pumping water well at a faster pace than groundwater normally flows, where there is no pumping water wells. While Sandoval County has examples of large, persistent cones of depression around Rio Rancho and other cities (Powell and McKean, 2014; and Rinehart et al., 2016), smaller cones of depression are common around water wells serving as domestic, mutual domestic, agricultural and small municipal supply wells (Rinehart et al., 2016). Generally, natural groundwater flow across Sandoval County is relatively slow, with groundwater ages of 100s to 1000s of years (Phillips et al., 1986; and Plummer et al. 2004). Near streams and rivers, these ages, and the corresponding flow rates, may be on the order of months to 10s of years (Rinehart et al., 2016). In cones of depression, transport times are accelerated, on the order of months to years. These faster transport times increase the inherent susceptibility of water wells to contamination.

Increasing numbers of studies since the advent of horizontal drilling combined with hydraulic fracturing have focused on the frequency of leaking wellbore contaminating groundwater supply wells (Jackson et al., 2013; Vidic et al., 2013; Davies et al., 2014; Vengosh et al., 2014; Sherwood et al., 2016; EPA, 2016; and Nicot et al., 2017). In regions with ongoing unconventional development, studies have taken place, but the source of the hydrocarbon is not always identifiable due to lack of pre-development geochemical data. However, it appears that there is a chance (5%) of stray methane leaking into the aquifer after horizontal drilling and hydraulic fracturing, generally by wellbore leaks, over the long term (>5 years; Vengosh et al., 2014). Beyond horizontal distances of ~1 mile (1.5 km) from the oil and gas well, the probability of contamination is low (Davies et al., 2014; and Vengosh et al., 2014). This distance reflects both the leakage rate and the transport rate into the water well. While this is beyond the resolution of this study, water well susceptibility to contamination from outward leakage from oil and gas wellbores is defined as being high if the well is closer than 0.6 miles (1 km) to an oil and gas well, moderate between 0.6 and 1 miles (1 km to 1.5 km), and low beyond 1 mile (greater than 1.5 km). This means that the susceptibility to outward leakage from boreholes is moderate to high within 1 mile of wells associated with cities, towns and homesteads throughout Sandoval

County. Additionally, much of Rio Rancho and Rio Rancho Estates will have a high susceptibility because of the density of municipal and domestic wells.

It is to be emphasized that the hazard from outward leakage is primarily a function **not** of the horizontal completion portion of the well, but of the degradation over time of the vertical well casing. The more oil and gas wells drilled through the aquifer, the greater the likelihood of an instance of borehole leakage occurring simply because of the increased number of wells.

One of the primary susceptibility factors is whether the oil and gas reservoir is pressurized to the point that its fluids can migrate upward into the aquifer if given a fast path, such as a fault, fracture or leaky wellbore. The primary risk factor is whether or not the oil and gas reservoir is overpressured, i.e., has enough pressure and buoyancy for oil and gas to rise to the surface from depth. These pressures vary with depth, so normally a pressure gradient in the reservoir is compared against the hydrostatic pressure gradient, or pressure gradient caused by the weight of a column of water pressure gradient. Reservoir over-pressures are also the primary risk factor for long-term leakage along permeable faults and fractures that may be connected during hydraulic fracturing of the well; this hazard is already considered in the stand-off distances used above. For contamination by long-term (years to decades) upward flow along degraded oil and gas vertical well casings, underpressured to normally pressured (less than 0.43 psi/ft) reservoirs are considered to have low susceptibility, moderately overpressured reservoirs (between 0.43 psi/ft to 0.70 psi/ft) to have moderate susceptibility, and highly overpressured reservoirs (>0.70 psi/ft) to have high susceptibility. The transition between moderately overpressure to highly over-pressured is based on the increased chance of unexpected failure as hydrostatic pressures approach lithostatic stress (Zoback, 2010), where there is an increased chance of fracture propagation upward from the reservoir.

In regions without oil and gas development, it is difficult to assess the reservoir pressure gradient. There is little data outside of the San Juan Basin on reservoir pressure gradients in the Mancos Shale. In the San Juan Basin, the oil and gas reservoirs are generally underpressured or normally pressure (Ridgeley et al., 2013), making the susceptibility to upward flow along oil and gas well casings low. In the Albuquerque Basin, there is some controversy about the pressures in the Mancos Shale reservoirs. At shallower depths (6,000 ft), pressure measurements show that the Mancos Shale is normally pressured (0.41 psi/ft; Johnson et al., 2001). Below this depth, there are not direct pressure measurements in the Mancos Shale. In the Dakota Sandstone immediately below the Mancos Shale at depths consistent with oil and gas production in the Albuquerque Basin (see above), the Dakota Sandstone is normally pressured. Based on drilling mud weights from wells drilled before 1990, Johnson et al. (2001) tentatively suggest that the Mancos Shale is moderately overpressured (0.519 psi/ft). However, it was common practice before 1990 to drill with greater than hydrostatic mud weights, whether the reservoir was overpressured or not. This was to suppress blow-outs and cave-ins during drilling, a factor that Johnson et al. (2001) does not discuss. The mud weights used in wells across the Mancos Shale throughout the basin range from 9.2 lb at 3989 ft bgs to 11.1 lb at 19,350 ft bgs (Johnson et al., 2001). There is little to no trend in mud weight vs. depth, and, in most of the well records, mud weight remains constant throughout drilling. This argues that the increased mud weight was used as a precautionary measure, rather than a reflection of overpressures. In other words, it appears that the Mancos Shale reservoir pressure is likely normal-, not over-, pressured. Nonetheless, the study of Johnson et al. (2001) indicates caution should be used when drilling modern exploration wells in the Mancos Shale in the Albuquerque Basin. For this report a low susceptibility from reservoir pressures in the Albuquerque Basin is tentatively advanced.

The permeability of fractures and faults in the subsurface is difficult to assess. Normally, shales smear along faults, reducing the permeability of the fault. Also shales, including the Mancos Shale, at reservoir stresses (the ‘pressure’ caused by the weight of rock, not fluid, on the reservoir) and normal to slight overpressure, can ‘heal’ open fractures through a process called rock creep, or time-dependent ductile deformation (Bourg, 2015). Because of this, faults and fractures are not considered as likely, or highly susceptible, pathways for fluids upward into the aquifer. In both the San Juan Basin and in the Albuquerque Basin, this assumption is supported by the multiple, overpressured water-bearing strata (also known as confined aquifers) layered on top of each other while being cut by fractures and faults (Kelley et al., 2014).

However, there is evidence of long-distance flow of fluids along faults in Sandoval County, particularly along the margins of the different basins and mountain ranges. In the northern Rio Puerco Transition Zone and the eastern San Juan Basin, there are a series of carbonic springs along the Nacimiento Fault south of Sierra Nacimiento (McGibbon, 2015). These springs are fed by volcanically sourced CO_2 from the Jemez Mountains. This suggests that the Nacimiento Fault zone at the western base of the Sierra Nacimiento is a permeable fault zone and should be avoided for oil and gas development. Other carbonic springs are present along the flanks of the Rio Grande valley south of Sandoval County and in the Jemez Mountains (Trainer et al., 2000). These are signs that major fault zones act as upward flowpaths. The fluid compositions are consistent with deeper, non-Rio Grande sources (Trainer et al., 2000; McGibbon, 2015). However, as mentioned in the main report, most aquifers in geologically similar areas along the flanks of the Rio Grande rift do not show signs large amounts of upward flow. Rather, there are stacked, hydraulically separate aquifers, suggesting that there is compartmentalization of the aquifer by faults rather than focused transmission of fluids along faults (Connell, 2008a, b; Riesterer et al. 2008; Riesterer and Drakos, 2008; and Kelley et al., 2014).

One challenge in assessing the susceptibility of groundwater contamination from oil and gas operations in Sandoval County is that aquifers may need to be developed in the future, but may have limited current water use or development. This is the case for a basin-fill aquifer west of Rio Rancho in the Albuquerque Basin; this aquifer is currently being developed as Rio Rancho's future water supply and has permitted but not drilled wells (Souder, Miller and Associates, 2013; M. Springfield, personal communication, 2018). These regions form the future water supply for the Rio Rancho area. Because oil and gas development carries water contamination hazards that increase through time (i.e., aging of well casings, tanks and pipelines), it was decided to consider the susceptibility of groundwater contamination of the Rio Rancho Estates region as if it has already been developed.

Criteria for susceptibility from subsurface contamination are summarized in Table S1. In the regions of Sandoval County with oil and gas potential, which consists of the San Juan Basin and local regions of the Albuquerque Basin, susceptibility to subsurface contamination are low. This is primarily because of the great (>1,900 ft) thickness of tight shale between the target reservoir, Mancos C, and the freshwater aquifers, and because of current standards of oil and gas well completions through aquifers. However, given many water wells supplying communities, the degradation of steel and cement through time, and normally to possible moderate overpressures seen in the Mancos Shale in the Albuquerque Basin, the susceptibility is medium to high, with densely populated regions having high susceptibility.

Susceptibility to surface contamination

Contamination from surface spills is a common groundwater contamination pathway. Oil and gas operations attempt to limit spills by putting in engineering controls for truck and train transport, testing integrity of tanks and pipelines, and having leak control at the well head. However, spills of hydrocarbons, produced waters and hydraulic fracturing fluids still occur. In their broad assessment, the EPA (2016) found that reported spills of hydraulic fracturing fluids ranged in volume from 5 gallons (19 L) to 19,320 gallons (73,130 L; EPA, 2016 and Maloney, 2017). To put this in an agricultural perspective, 20,000 gallons is 0.06 acre-feet.

Patterson et al. (2017) disaggregated data more than the EPA (2016) report and included spills from freshwater tanks, not just from oil and gas and produced water tanks. They found a median spill volume in New Mexico of 1300 gallons between 2005 and 2014. The maximum oil and gas releases (98,280 gallons) came from a well-head blow-out. Spill rates (4% of wells and other oil and gas facilities) are greatest in the first 3 years of well life and decline to 1% or less after 3 years; this may be controlled sampling bias caused by the increased production in the Permian Basin (Patterson et al., 2017). Most commonly, spills in New Mexico occurred at tanks (either leaking or other operations; Patterson et al., 2017).

This study provides different levels of susceptibly to surface contamination as a function of local area depth-to-water and whether the potential oil and gas well is in a floodplain. Locations in a valley bottom or floodplain increase the susceptibility of groundwater contamination from a surface spill. Flood events can mobilize the contaminant and drive it into the shallow groundwater. Depths-to-water in floodplains can vary dramatically seasonally, increasing the odds of entrainment of a surface spill that has infiltrated. Location in a floodplain or valley bottom is considered to have a high susceptibility for surface spills leading to groundwater contamination. Site-specific factors should control exact stand-off distances from the floodplain before grading to a low susceptibility to spills entering the floodplain; the susceptibility decreases above the spatial resolution of this study, so in this report susceptibility for groundwater contamination from surface spills in floodplains is simply considered as either high or low.

A surface spill can enter the groundwater through two primary pathways: downward infiltration through unsaturated zone to the water table, or the water table rising and intersecting an otherwise relatively static contaminant plume (Vidic et al., 2013; EPA, 2016; Maloney et al., 2017; and Patterson et al., 2017). There is a great deal of uncertainty surrounding both of these pathways. However, using spill volumes with common but conservative hydraulic properties, historical studies, and experience of groundwater level changes around New Mexico, physically-based susceptibility and risk thresholds were determined.

Rinehart et al. (2016) estimated groundwater level and storage changes over the last 60 years across the Rio Grande basins at decadal time-steps. As part of this, Rinehart (co-author on this report) reviewed thousands of groundwater level hydrographs from around the Rio Grande valley, including the Albuquerque Basin in Sandoval County. All of these hydrographs are available as part of Rinehart et al. (2016). Overall, it was found that water-levels have been declining from decade to decade around the state, particularly distal from floodplains. In the floodplain, the combination of shallow depth to water, with water levels closely tied to the river, and return flows from flood irrigation stabilized the water table. In the Albuquerque Basin, stability of shallow water tables along the floodplain were found but dramatic declines (deeper water tables) occur away from the river (Bexfield and Anderholm, 2000; Powell and MacKean, 2014; and Rinehart et al., 2016). Distal to the Rio Grande, around Rio Rancho and along the western edge of the Sandia Mountains, water tables are deep (> 100 ft to water) and have gotten deeper, often more than 100 ft deeper. Seasonal water table oscillations in the floodplain, on the Llano de Albuquerque or in the eastern piedmont deposits are at most 30 ft. Even around artificial recharge sites in eastern Albuquerque, water tables have only risen tens of feet. In western Sandoval County, where there was enough data, Rinehart et al., (2016) found there was little groundwater level change. Water tables are stable or declining. As is seen elsewhere in the state, the largest water table oscillations occur along valleys, with changes up to 50 ft in extreme cases, with more common maximum oscillations of 10-15 ft (Rinehart et al., 2016).

The combination of depth-to-water, regional decadal declining trends, and seasonal water level variability amounts combine into a set of susceptibility thresholds. In areas with depths to water shallower than 50 ft, long-term and intra-annual water level variations are more likely to come near (10s of ft) or intersect the surface, making high susceptibility of groundwater contamination from a surface spill. Between 50 ft and 100 ft, it is possible but unlikely for the water table to rise near the land surface either in the short term or long-term, making regions with depths-to-water of between 50 ft and 100 ft moderately susceptible to groundwater contamination from a surface spill. With groundwater deeper than 100 ft below the land surface, it is unlikely for the groundwater table to rise to the surface, especially considering that long-term planning around Rio Rancho holds the water table near or below the current depths (Souder, Miller and Associates, 2013). This implies that regions with groundwater depths of > 100 ft have a low susceptibility to groundwater contamination from surface spills.

However, the groundwater rising into a spill's plume is only half the issue. The spill also infiltrates from the surface to the groundwater table. For a surface spill or any other fluid to percolate from the land-surface to the aquifer, it must move through sediments whose pores are not filled, or saturated, with water. This is called the unsaturated or vadose zone. The properties that control the rate of infiltration are a function of the degree of saturation (how full the pores are), the initial moisture condition of the soil, the grain-sizes and pore-sizes of the unsaturated material (sediment), the density of the infiltrating fluid, the contact angle of the fluid and minerals, and the depth and duration of ponding at the surface during the spill (Bear, 1972; Hillel, 1998; and Jury and Horton, 2004). Because of the number of controls on unsaturated fluid flow, other risk assessments of similar scale to this study have called for site specific assessments (EPA, 2016). However, these have generally been studies with more refined, quantified susceptibility and risk metrics. For this study, where low, moderate and high susceptibility and risk are grouped coarsely, some general scenarios constrained by spill volumes, common work areas, and common soil textures for soils outside of floodplains and arroyos around Sandoval County are considered.

As mentioned above, reported oil and gas spills nationally have moderate volumes and occur over short periods (days) of time. Additionally, spills are constrained in area, which decreases the susceptibility spill run-off entering water supplies and the difficulty of cleaning the spill site up, but over the long-term (months to years) increases the penetration depth of the contaminant through the soil (Fetter, 1999; and Hillel, 1998).

Estimating infiltration rates is a complicated function of soil texture, initial soil saturation, depth and duration of ponding of the spill, degree of saturation of the wetting front, and other factors. Site-specific modeling is needed to fully assess either the susceptibility particular regions to downward-infiltrated groundwater contamination. Away from the alluvial valley bottoms and mountains, the build-up of calcium carbonate in the soils indicates that over pedologic (soil-forming) time (1000s years), extreme rainfall events do not penetrate loamy and loamy sandy soils more than 10 m, as evidenced by the build-up of nitrate salts (32 ft; Gile et al., 1981, Gile et al., 1995; and Walvoord et al., 2003). While this is different than a point source of contaminant infiltrating down, extreme rainfall events can last for weeks at moderate to high intensities, flooding much of the land-surface during the event, driving infiltration close to its maximum long-term rate, and precluding any horizontal redistribution of fluid.

This penetration depth of 10 m (32 ft) is supported by the long-term infiltration rates of Hillel (1998). For sandy soils, Hillel (1998) reports infiltration rates of > 1.5 ft/d; these values can vary by as much as an order of magnitude in Sandoval County (Soil Survey Staff, 2008). Much of sediments and soils of Sandoval County, however, are sandy loams, with a rough maximum long-term infiltration rate of 0.7 to 1.5 ft/d (Soil Survey Staff, 2008). This means, as a worst case scenario, in coarse sands, a large, high-volume, concentrated, long-term spill could penetrate 10s of feet in days. However, much smaller volumes and durations of spills are more typical (EPA, 2016; Patterson et al., 2017), still limiting susceptibilities from downward flow. In more normal, loam soils, a pond of contaminant would require ~30 days to penetrate 50 ft at its maximum rate, and ~60 days to penetrate 100 ft. Spills are required to be reported within 14 days to NMED (Patterson et al., 2017).

Given a reasonable worst-case spill volume of 20,000 gallons (EPA, 2016; and Maloney et al., 2017), the depth of soil that could be penetrated given different spill areas was evaluated. Because once the surface is no longer ponded (i.e., the total volume of spill has infiltrated into the soil) infiltration slows down dramatically (Hillel, 1998; and Jury and Horton, 2004), this calculation also helps constrain the susceptibilities to downward contamination. A rough approximation of the depth of penetration of contaminant in the soil can be found by dividing the volume by the area of the ponding/spill and the volumetric contaminant content:

$$d=V/\theta_{cont}A, \qquad (1)$$

where d is the penetration depth, V is the volume of the infiltrated spill, A is the area of the spill, and θ_{cont} is the volumetric contaminant soil content (fraction of soil volume filled by contaminant). For a 20,000 gallon (2673 cubic ft) spill in a 1000 sq-ft area (this would lead to 1-ft of initial ponding) and assuming an conservative volumetric soil contaminant content of 0.05 (5% of soil has contaminant by volume, or about 12% of the pore space for a loamy sand or sandy loam; this is roughly background soil moisture content (Walvoord et al., 2004)), the fluid would penetrate 53 ft. This surface area, roughly 10 yds by 10 yds, is smaller than most worksites and is likely less than the area of a large spill (Davies et al., 2014). This means that at 50 ft, an infiltration front from a contaminant spill would have reached a background level of moisture—this is unlikely to happen as the infiltration front will slow more and more as it approaches the background, initial soil moisture (Jury and Horton, 2004). This analysis shows that for the largest reported spill from oil and gas operations in the U.S., it is unlikely for the contaminant to penetrate more than 50 ft. As a measure of safety and to account for grain-size variability, 100 ft is considered to have a low susceptibility to surface infiltration of contaminants. Regions with a highly permeable unsaturated zone (sands and arroyo bottoms) are considered high susceptible because of the unpredictable, high infiltration capacity (Jury and Horton, 2004) and the likely focused recharge during stream flood events.

It is important to note that these infiltration calculations assume (1) brine being a likely contaminant, (2) a short (< 1 month) spill. Long-term (years to decades), undetected spills, such as the Kirtland Fuel Spill, can have extremely deep infiltration depths.

For assessment of downward, surface contamination of groundwater, it is considered that a depth-to-water of less than 50 ft has high susceptibility, between 50 ft and 100 ft has a moderate susceptibility, and a depth-to-water more than 100 ft has low susceptibility. Arroyo and valley bottoms are uniformly considered to be high susceptibility. Thresholds defining regional susceptibility to downward contamination are summarized in Table S1.

Figure S23 shows a refined map of susceptibility of groundwater to contamination from oil and gas development. In general, this map shows that much of Sandoval County has a low susceptibility to contamination. Many of the regions that are most susceptible do not have oil and gas potential. In the San Juan Basin, regions that have medium to high upward contamination susceptibilities and oil and gas potential are around the edges of the Sierra Nacimiento and

Jemez Mountains, where there are documented transmissive faults, and in the populated Albuquerque Basin, where high water supply well density combined with a moderately overpressured oil and gas reservoir increase the long-term susceptibility to groundwater contamination. Regions in floodplains, arroyos, valley bottoms and regions with shallow water tables have high susceptibility to contamination, including along the base of the Sierra Nacimiento, the Rio Grande Valley, the Placitas-Hagan Embayment-Sandia region, and other major river valleys (Fig. S23).

Risk

Estimation of risk of a hazard must balance the susceptibility of a region to that hazard and the costs, both monetary and value-driven, of the hazard occurring in the region. This means that risk is necessarily more difficult to assess than susceptibility. Similar to the approach used for estimating the susceptibility to groundwater contamination, risks are grouped into low, moderate and high based on the likely consequences of serious, not commonplace, spills. The largest scales of the event include long-term upward leakage, which have the potential to happen in the Albuquerque Basin because of the moderate overpressures of potential reservoirs, if there is long-term leakage of surface storage facilities, and if there was a large (tractor-trailer or larger) spill. Despite the relatively uncommon occurrence of spills and leaks, oil and gas operations involve moving significant volumes of hydrocarbons and other chemicals which contain contaminants known to negatively impact human health (EPA, 2016).

Hydrocarbon releases in groundwater are very difficult to remediate (Fetter, 1999). Parts of the liquid phase of hydrocarbons are denser than water and can sink into an aquifer, leaving a dispersed but sinking trail of dense hydrocarbons in the aquifer (Bear, 1972; and Fetter, 1999). Other liquid hydrocarbons are not as dense as water. An increase in 'stray gas,' or methane, has been found to occur around wells, including newer wells. Stray gas may contain constituents that are harmful to humans, but is mostly made of methane (Vidic, et al., 2013; and EPA, 2016). In some cases reports of stray gas may have already been present due to biogenic methane, but that does not preclude other wells leaking thermogenic, or reservoir gas (e.g., Sherwood et al., 2016).

Stray gas and lighter-than-water fluids can be pulled to pumping water wells if there is a leak (Sherwood et al., 2016). This is caused by the pressure gradient caused by groundwater pumping. If groundwater pumping stops, stray gas is thought to simply leak from the groundwater table surface into the atmosphere. Lighter-than-water fluids will rise to and then rest on the water table, accumulating and presenting a long-term hazard. Denser-than-water fluids will sink into the water, falling deeper and deeper into aquifer.

Both for fluids rising through the aquifer and fluids falling through the aquifer, concentrations of these hydrocarbons remain trapped in the aquifer materials (i.e., rocks and sediments; Bear, 1972; and Fetter, 1999). This can happen either by diffusion of the constituents into water or by small parcels of the fluid being trapped in narrow pore throats (the narrow 'necks' or spaces between sand grains; Bear, 1972). Trapped hydrocarbons in the aquifer can be mobilized later during natural or pumped groundwater flow (Fetter, 1999). This leads to a long-term hazard after large spills and leaks (Fetter, 1999). Because of the trapping of non-aqueous phase fluids in tight pores and the dispersion of the plume across part of the aquifer while the fluid is emplaced, it is challenging to remove these fluids from the aquifer (Fetter, 1999). It requires extensive and expensive pumping of the aquifer, followed by treatment and disposal of the water (Hillel, 1998; and Fetter, 1999).

Hydrocarbon spills also commonly remain trapped near the surface, in the vadose or unsaturated zone (Hillel, 1998). Similar to being trapped in the aquifer, the hydrocarbons 'cling' to sediment grains and in pore throats. This phenomenon, too, presents a long-term hazard—these trapped fluids may slowly sink down into the aquifer or be driven down during water infiltration (Hillel, 1998). Some of these fluids may volatize off or be reduced by microbial activity with time; volatilization may present an inhalation hazard for people above the spill (Fetter, 1999).

'Frac'-fluid, or the water with additives used to hydraulically fracture wells has a range of constituents, which have largely been documented (Vidic et al., 2013; and EPA, 2016). Among a long-list of additives, several are identified as being harmful to humans. Another contaminant source is the hydrocarbon- and metal-rich, usually salty produced water that is generated with oil and gas (EPA, 2016). These produced waters are often very saline, have multiple harmful constituents, and could have negative health effects if they come in contact with drinking water supplies if they enter the aquifer in large volumes. Both frac-fluids and produced waters present a hazard that may be difficult to manage. While most constituents are not trapped in pore throats, subsurface flow of the spill can diffuse and disperse into the aquifer as it flows, spreading the plume, making it more and more difficult to clean up with time and more and more difficult to map in the subsurface. This spreading requires pumping significantly more water than the spill volume in order to remediate the groundwater.

In light of the possible significant impacts on human health of a large but unlikely accidental release, this report is conservative in assessing risks. If there are oil and gas wells within 1 mile of municipal wells, near streams, arroyos or rivers, or near domestic or agricultural wells, the risks are high. If there is a moderately high density of water wells (>1 per land section), then the risk rating is the susceptibility upgraded one level (e.g., from Low susceptibility to Medium risk). Similarly, if homes, communities and agriculture are solely dependent on groundwater, the risk rating is the susceptibility rating increased by one level. This reflects the challenges and costs of aquifer remediation, the global, long-term average rate of occurrence of vertical well-bore leakage, and the always present, low-hazard of accidental releases during normal oil field operations. Permitted but not drilled municipal wells, such as those that may provide the future water supply of the City of Rio Rancho and Rio Rancho Estates (Souder, Miller and Associates, 2013) are included in this higher risk category. Risk thresholds and logic are summarized in Table S2.

Away from regions defined as high risk because of their proximity to current or future water supplies, or to streams, other regions that could be high risk by default are around the bounding faults of the Sierra Nacimiento and Jemez Mountains (Fig. S13), where there is strong evidence of faults with long-distance pathways. Additionally, the Placitas-Hagan Embayment-Sandia Mountain Region has little if any depth to the Mancos Shale, shallow (< 50 ft) water tables and an abundance of ephemeral washes, all leading to an initial assessment of high risk to both surface and aquifer contamination. However, these regions have low oil and gas potential, which makes the risk potential low (Fig. S24).

In the remainder of Sandoval County, risk maps directly onto susceptibility (Fig. S24). In the oil and gas producing San Juan Basin, susceptibility and risk is generally low. In the Rio Puerco Fault Zone, Sierra Nacimiento and Laramide Uplift, Jemez Mountains, and Placitas-

Hagan Embayment-Sandia Mountains regions, the susceptibilities may be low to moderate with concentrations around wells for homesteads, towns and streams. However, these regions have low oil and gas potential, making the overall risk low. Away from surface streams and drinking water wells, contamination risk in the San Juan Basin is low, because of the deep depth-to-water, underpressurized oil / gas reservoir, lack of faults, and low population density.

The Albuquerque Basin in Sandoval County has moderate oil and gas potential in a few local areas. It also has a high population and is extensively faulted—though it is assumed that the multiple layers of shales between the reservoir and the aquifers mitigate this hazard. In these groundwater-dependent populated regions, risk is assessed to be high locally (<1 mile) from current or permitted drinking water wells and an increased risk compared to susceptibility throughout the basin. This includes most of the area of the City of Rio Rancho and much of Rio Rancho Estates. However, because of uncertainty in the placement of future domestic drinking water wells in Rio Rancho Estates, the general risk in this region—which overlies a moderate potential oil and gas region—is assessed as moderate, though it grades to low to the west across into the Rio Puerco Transition Zone. In general, the long-term hazard of oil and gas development in the Albuquerque Basin is higher both because of the greater water well density and because of uncertainty about the Mancos Shale reservoir pressures.

Summary of risk and susceptibility of groundwater contamination

The primary goals of this supplemental report were to provide an enhanced analysis of the oil and gas potential of the Albuquerque Basin part of Sandoval County and to clarify the logic and metrics used to define the susceptibility and risk of groundwater contamination by oil and gas development in Sandoval County. In the process of clarifying the susceptibility and risk metrics, several revisions were made to the groundwater contamination risk assessment:

- The hazard presented by shallow water tables has been re-emphasized.
- The permitted but undrilled wells of Rio Rancho Estates that may serve as the future water supply of this development and the City of Rio Rancho increase the risk to moderate to high throughout the Albuquerque Basin.

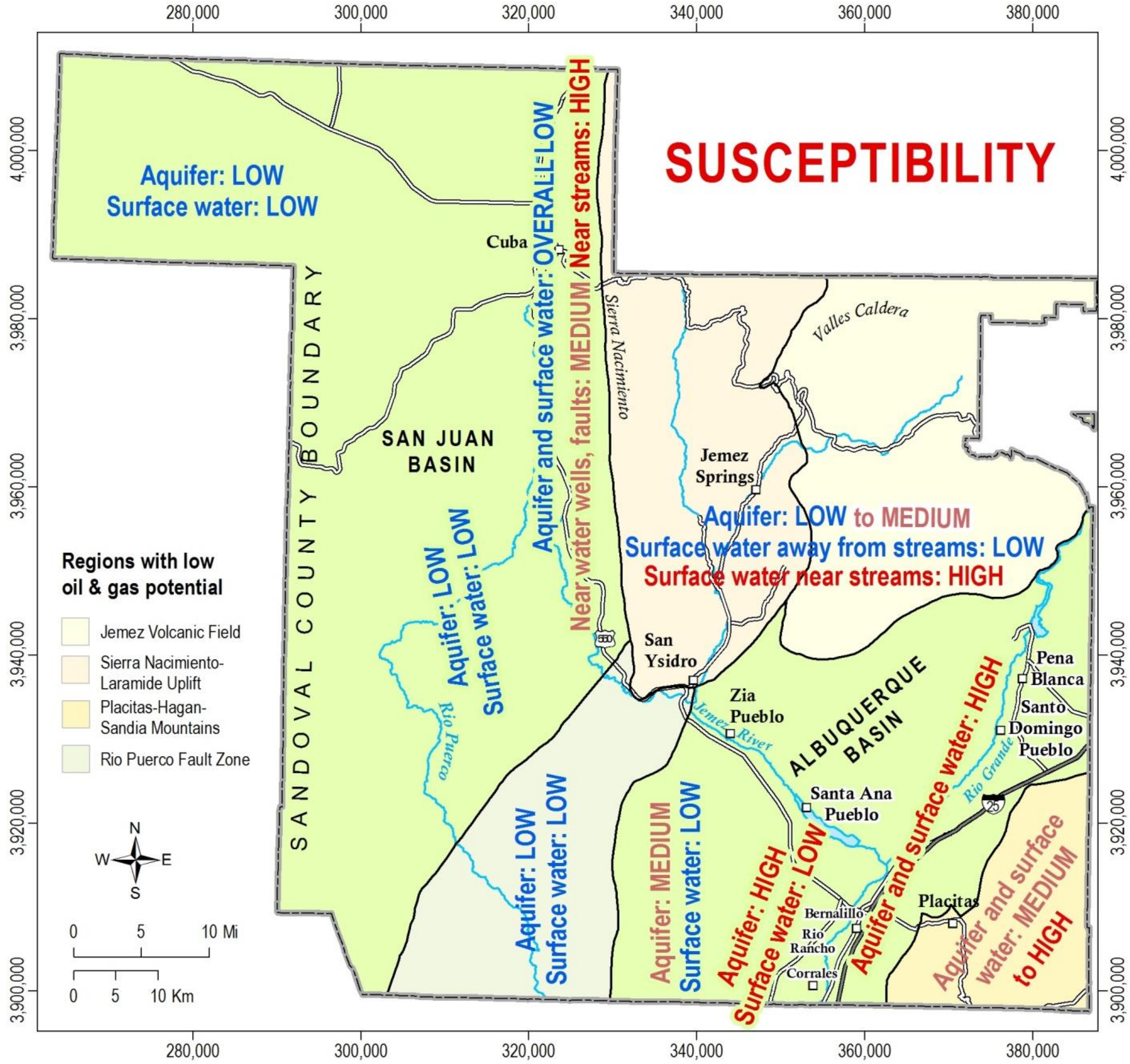

Figure S23. Map indicating different regions of **susceptibility** to groundwater contamination across Sandoval County. Susceptibility is proclivity or the likelihood of a hazard occurring without consideration of the costs or frequency of that event. Susceptibilities range from low (blue), to medium (orange), to high (red). Separate susceptibilities for sub-surface, or aquifer contamination pathways, and for top-down, or surface water contamination pathways are shown.

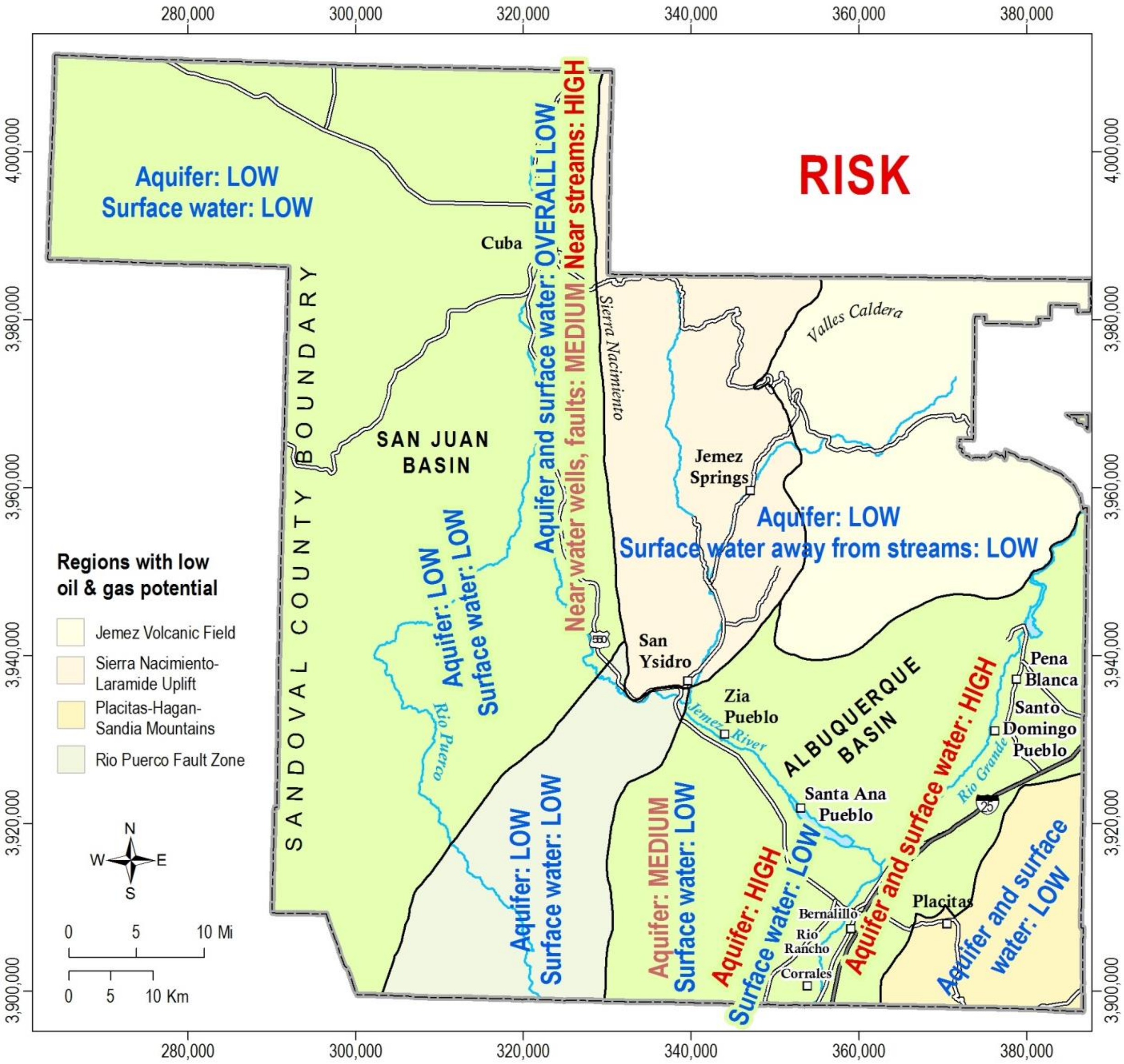

Figure S24. Map indicating different regions of **risk** to groundwater contamination from oil and gas development across Sandoval County. Risk includes both the susceptibility, or proclivity to a hazard occurring and the costs, or consequences of that occurrence. Risks range from low (blue), to medium (orange), to high (red). Separate risk for sub-surface, or auifer contamination pathways, and for top-down, or surface water contamination pathways are shown.

Table S1. Summary of susceptibility thresholds.

Description	Susceptibility Thresholds		
	Low	Medium	High
Sub-surface, or aquifer susceptibility controls			
Vertical thickness of sealing formation above reservoir formation	>1,900 ft	400 ft - 1,900 ft	<400 ft
Horizontal distance to fault	> 1,500 ft	500 ft - 1,500 ft	< 500 ft
Horizontal distance of vertical portion of oil and gas well to water well	> 5,280 ft	3,300 ft - 5,280 ft	< 3,300 ft
Conductive fault/fracture	No current evidence	-	Current evidence of deep connection
Reservoir pressure	< 0.42 psi/ft	0.42 psi/ft - 0.8 psi/ft	>0.8 psi/ft
Number of sealing formations >1,900 ft above reservoir	>1	-	1
Water well location	> 1 mile	-	< 1 mile
Surface susceptibility controls			
Depth-to-water (below ground surface) to protect from groundwater entrainment	> 100 ft	50 ft - 100 ft	< 50 ft
Depth-to-water (below ground surface) to protect from surface infiltration	> 100 ft	50 ft - 100 ft	< 50 ft
Arroyo bottom, floodplain or stream	-	-	If yes, then High

Table S2. Summary of determination of risk levels.

Description	Risk
No or low oil and gas potential	Low risk
Well density > 1 well per section	Increase risk one level from susceptibility
Wells within 1-mile of oil and gas development	High risk
Dependence on groundwater supply for drinking water	Increase risk one level from susceptibility
Presence of streams, rivers, other surface water	High risk
Otherwise	Use susceptibility level

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