Diffusivity Mapping of Fracture Interconnections

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Abstract

Fractures at individual wells can be readily detected in core, or inferred from double-porosity hydraulic test responses. Establishing continuity of fracturing (interconnectivity) from one well to another is more difficult, particularly as the scale of investigation increases. Groundwater investigations of the Culebra Dolomite Member of the Rustler Formation at the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico have used estimates of hydraulic diffusivity to identify regions interconnected by fractures over an area of approximately 15 km by 25 km.

Hydraulic tests and other information from 66 Culebra well locations around the WIPP site have shown evidence of fracturing at 33 of the locations, allowing a rough map of fractured and unfractured regions to be drawn. With distances between fractured and unfractured well locations being as low as 0.4 km and many areas with neighboring wells greater than 1 km apart, however, the continuity of the fractured and unfractured zones cannot be ascertained from single-well data alone. Hence, multiple pumping tests with overlapping areas of influence have been used to map the interconnections among wells.

Responses to pumping tests performed at 15 Culebra wells were observed at one to 13 other wells for each test, with distances between pumping wells and responding observation wells ranging from 395 m to 9.5 km. Because the directional distribution of the pumping rate is not known in a heterogeneous system, transmissivity (T) and storativity (S) cannot be inferred individually from the observation-well responses, but only as their ratio, diffusivity (D=T/S). Log_{10} diffusivities (in m^2/s) less than 0.2 appear to reflect porous medium (i.e., unfractured) connections between wells, while values greater than 0.2 reflect fracture connections. Mapping of interwell diffusivities has confirmed the presence of a continuous unfractured region of the Culebra extending from northeast to southwest across the WIPP site.

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Introduction

The Waste Isolation Pilot Plant (WIPP) is the U.S. Department of Energy's (DOE) deep geologic repository for transuranic (TRU) and mixed waste. The repository was constructed 655 m below ground surface in bedded halite of the Permian Salado Formation in southeastern New Mexico (Figure 1). Site-characterization activities began in 1974 and WIPP became a licensed, operating repository in March 1999. Groundwater studies at the WIPP site have focused on the Culebra Dolomite Member of the Rustler Formation because it is the most transmissive, continuously saturated unit above the repository and would provide the most likely groundwater transport pathway for radionuclides released from the repository by inadvertent human intrusion.

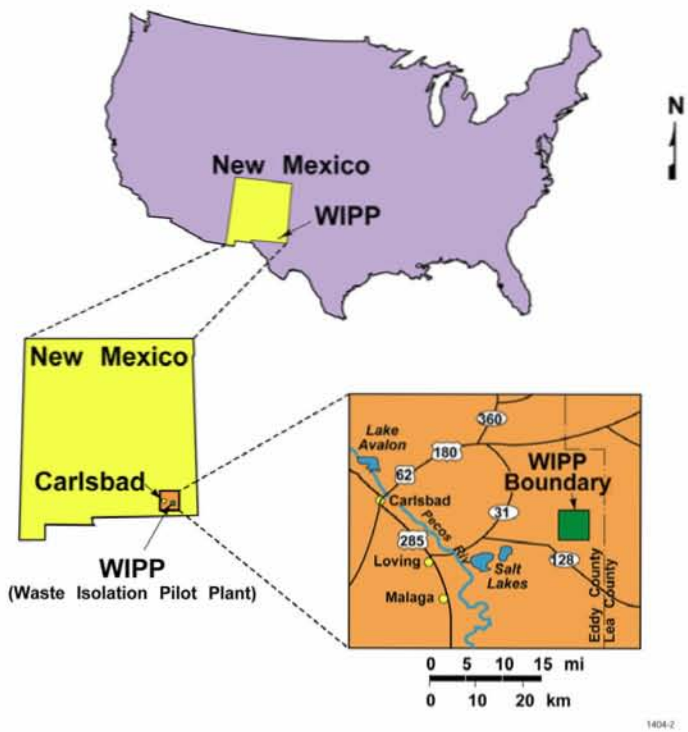

Figure 1. Location of the WIPP site.

The Culebra is a locally argillaceous and arenaceous, well- to poorly indurated dolomicrite approximately 7-8 m thick. It exhibits significant spatial heterogeneity in the types of porosity, the amount of fracturing, and the amount of porosity-filling cements (primarily gypsum, with some halite) that are present (Figure 2). Hydraulic testing at individual well locations has shown that the transmissivity (T) of the Culebra varies over more than six orders of magnitude (Mercer, 1983). Lower transmissivities are associated with low degrees of fracturing and pervasive porosity-filling cements and higher transmissivities are associated with extensive fracturing and little porosity-filling cements (Holt et al., 2005). Fractures in the Culebra are significant to WIPP because of their potential to act as "fast paths" for radionuclide transport.

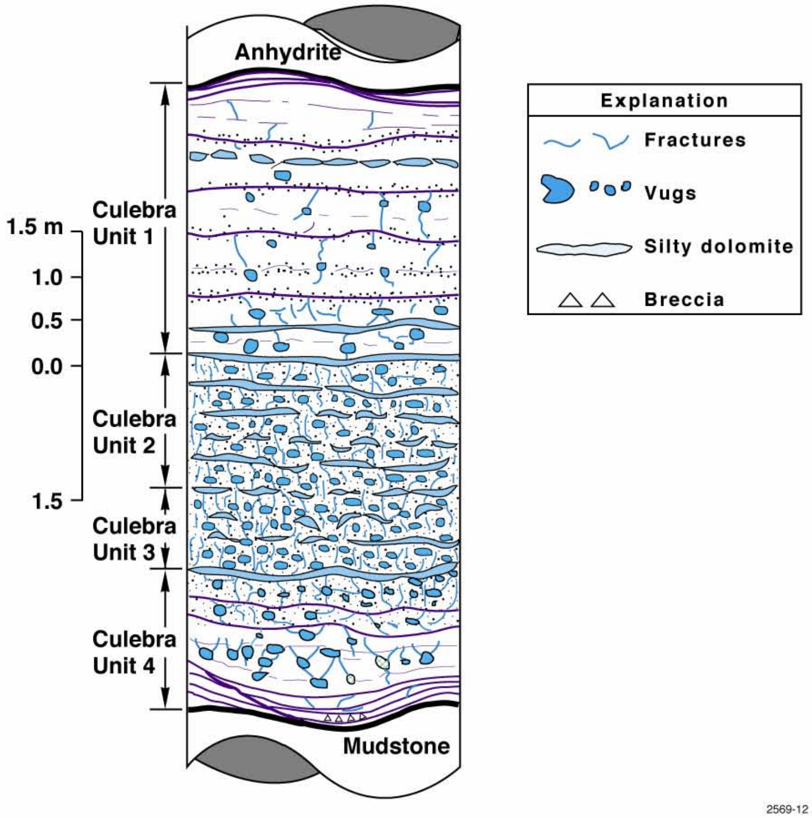

Figure 2. Typical Culebra section.

Holt et al. (2005) attribute the variation in Culebra T and fracturing to three principal factors: dissolution of the underlying Salado Formation, stress relief caused by erosion of overburden, and the presence or absence of gypsum (or halite) filling the available porosity. Dissolution of the upper Salado Formation has created a large subsidence trough, known as Nash Draw, to the west of the WIPP site (Figure 3). Within Nash Draw, evaporite karst is present in the sulfatic members of the Rustler Formation, and the Culebra is collapsed and broken. East of the WIPP site where the Culebra is deeply buried, few fractures are observed and both the fractures and varying amounts of the primary porosity of the Culebra are filled with sulfatic and/or halite cements. In the area between Nash Draw and the eastern boundary of the WIPP site, the presence and continuity of fracturing is hard to predict.

Hydraulic tests and other information from 66 Culebra well locations around the WIPP site have shown evidence of hydraulically significant fracturing at 33 of the locations, allowing a rough map of fractured and unfractured regions to be drawn (Figure 3). With distances between fractured and unfractured well locations being as low as 0.4 km and many areas with neighboring wells greater than 1 km apart, however, the continuity of the fractured and unfractured zones cannot be ascertained from single-well data alone. Hence, a method is desired that allows us to determine what portions of the Culebra are, and are not, interconnected by fractures without having to drill and test wells everywhere.

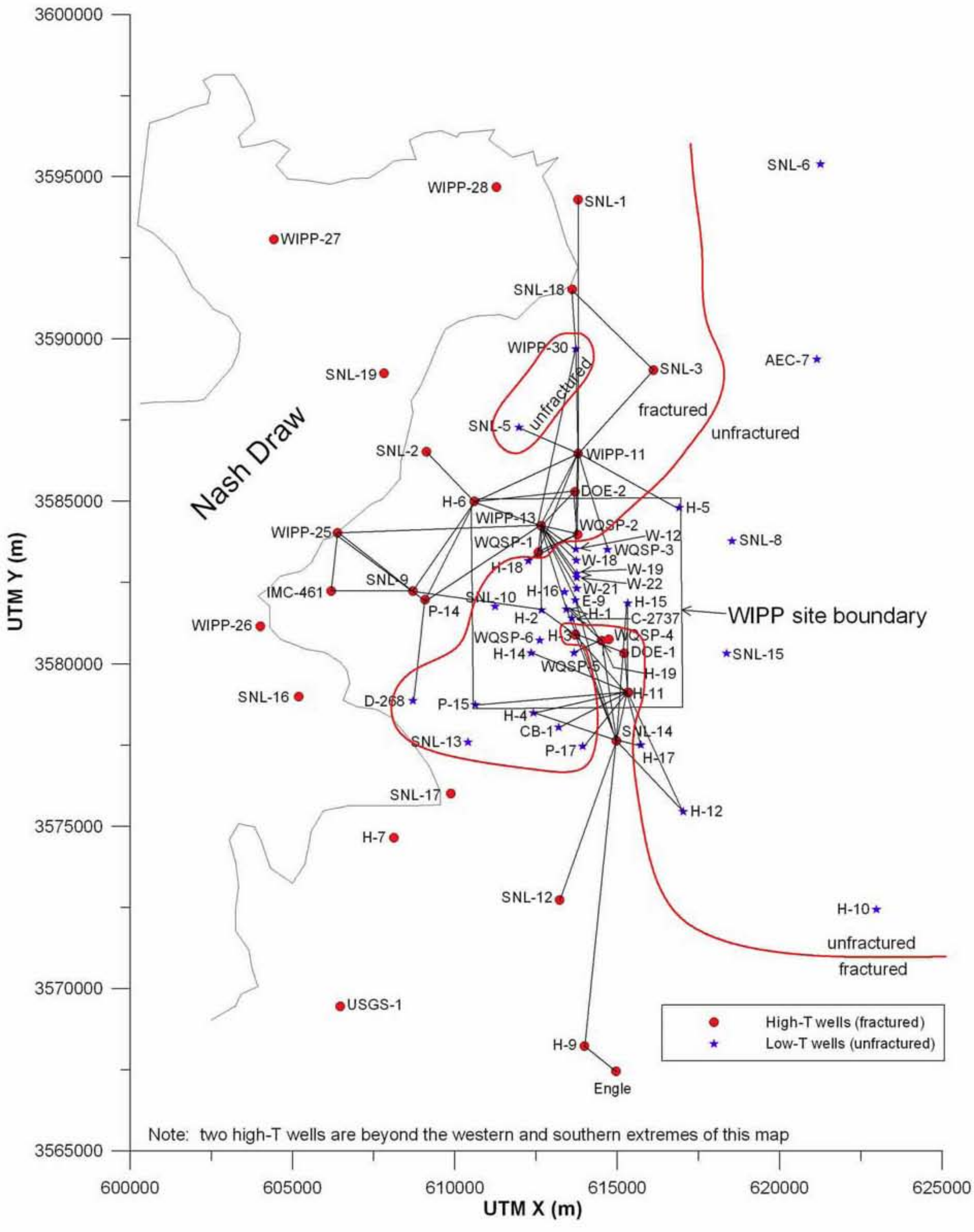

Figure 3. Locations of Culebra wells around the WIPP site. Lines connect well pairs for which diffusivity estimates are available.

Knudby and Carrera (2006) discussed the use of hydraulic diffusivity as an indicator of connectivity. Hydraulic diffusivity (D) is the ratio of transmissivity and storativity (T/S) and can be determined from the responses of observation wells to pumping tests in heterogeneous systems. In fact, only D, and not its constituent parameters T and S, can be determined from such tests because independent estimation of T and S requires knowledge of the areal distribution of flow during pumping, which is not known in a heterogeneous system. Generally speaking, higher values of D reflect higher degrees of connectivity.

Scores of pumping tests of the Culebra have been performed for WIPP since the 1980's. Many of the tests were of short duration, and responses were observed only at other wells on the same drilling pad (well separations of 10-43 m). But responses to 15 of the pumping tests were observed at one to 13 other wells for each test, with distances between pumping wells and responding observation wells ranging from 395 m to 9.5 km. A total of 69 pumping well-observation well response couplets are available, allowing us to perform a *post hoc* analysis using inferred values of hydraulic diffusivity as a measure of fracture connectivity.

Well Testing at WIPP

Approximately 90 wells have been completed to the Culebra at 66 locations in the vicinity of the WIPP site (Figure 3). Pumping tests have been performed in most of the wells, while slug tests and/or drillstem tests (DSTs) have been performed in the remaining, typically low-T, wells. Transmissivity values have been inferred for each of the wells from single-well test data, i.e., when the subject well was the tested well, not an observation well. Above a T value of approximately 6×10^{-6} m^2/s, the Culebra has been found to exhibit double-porosity (fractures and porous matrix) hydraulic responses (Gringarten, 1984; 1987), while below that value the Culebra appears to behave hydraulically as a single-porosity medium (Beauheim and Ruskauff, 1998). Figure 3 shows the locations of the Culebra wells around the WIPP site, with each well classified as either high-T (fractured) or low-T (unfractured).

Multiple Culebra wells were installed on the same drilling pad at nine locations, with well separations ranging from 10 to 43 m. Pumping tests were conducted at each of these locations, using the other wells on the drilling pad as observation wells. In all cases, interpretation of the observation-well responses confirmed the single- or double-porosity interpretation made of the pumping-well responses (Beauheim and Ruskauff, 1998).

During pumping tests at 15 Culebra well locations, responses were observed at observation wells on other drilling pads 395 m to 9.5 km away. Figure 3 shows the pumping well-observation well couplets for which we have data. Note that the pumping tests were conducted over a span of 20 years, during which many wells were added to the monitoring network while others were plugged and abandoned. Thus, not all of the wells shown on Figure 3 were available to serve as observation wells during all of the pumping tests.

The observation-well responses were simulated using the petroleum-industry well-test-analysis code Interpret2000® (or earlier versions) (Beauheim, 1986; 1987a,b; 1989; 2002; Beauheim and Ruskauff, 1998). Interpret2000 provides an optimized fit between the data and a user-selected analytical solution. The analytical solutions available incorporate wellbore storage and skin, single- or double-porosity conditions (with transient or steady-state interporosity flow), and a variety of boundary types and geometries.

A double-porosity medium is one in which the majority of the permeability is provided by fractures while the majority of the storage is provided by the porous matrix. During a hydraulic test, the high-permeability, low-storage (i.e., high diffusivity) fractures respond first, followed by the low-permeability, high-storage (i.e., low diffusivity) matrix. Depending on the contrast in properties and the location and time of observation, the fracture response and the matrix response may be distinguishable. On a log-log plot of pressure change and the derivative of pressure change with respect to log time versus the log of elapsed time (Figure 4), the pressure change trace shows a flattening while the derivative shows a minimum during the period when the pressure in the matrix is equilibrating with the already-lowered pressure in the fractures. The late-time stabilization of the derivative reflects the transmissivity of the total system. Generally speaking, double-porosity behavior is evident in high-T locations in the Culebra in pumping-well responses (e.g., Figure 4) and in the responses of observations wells on the same drilling pad as the pumping well (e.g., Figure 5). When it is evident over longer distances (e.g., Figure 6), the minimum in the derivative is usually not observed, but a temporary flattening of both traces is observed compared to single-porosity responses. Observable double-porosity responses over long distances represent a high degree of fracture connectivity between the pumping well and the observation well.

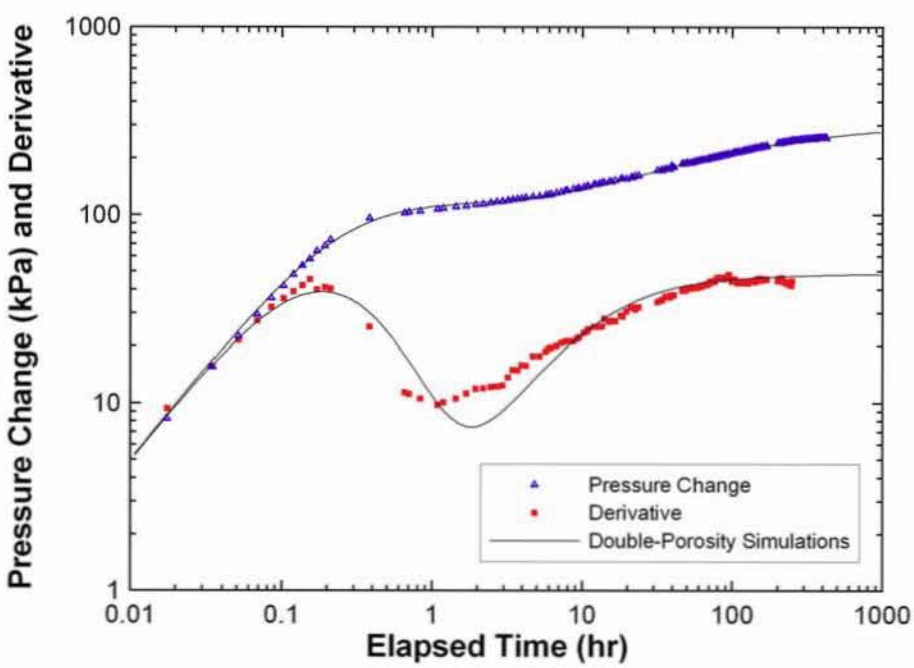

Figure 4. Double-porosity recovery response from pumping test at well DOE-1.

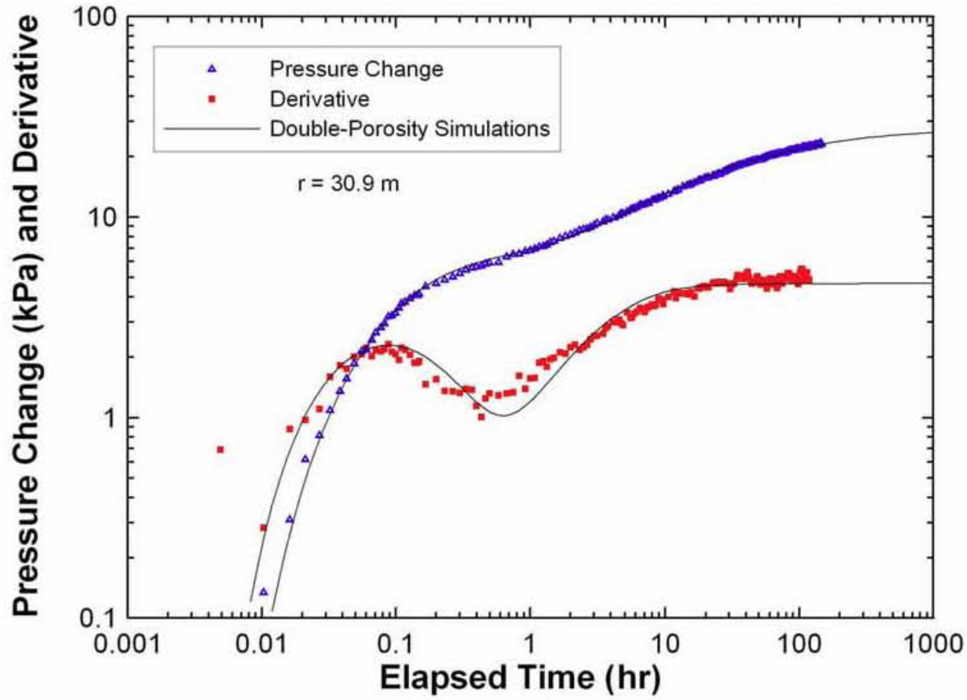

Figure 5. Double-porosity recovery response at well H-9c from pumping 30.9 m away at well H-9b.

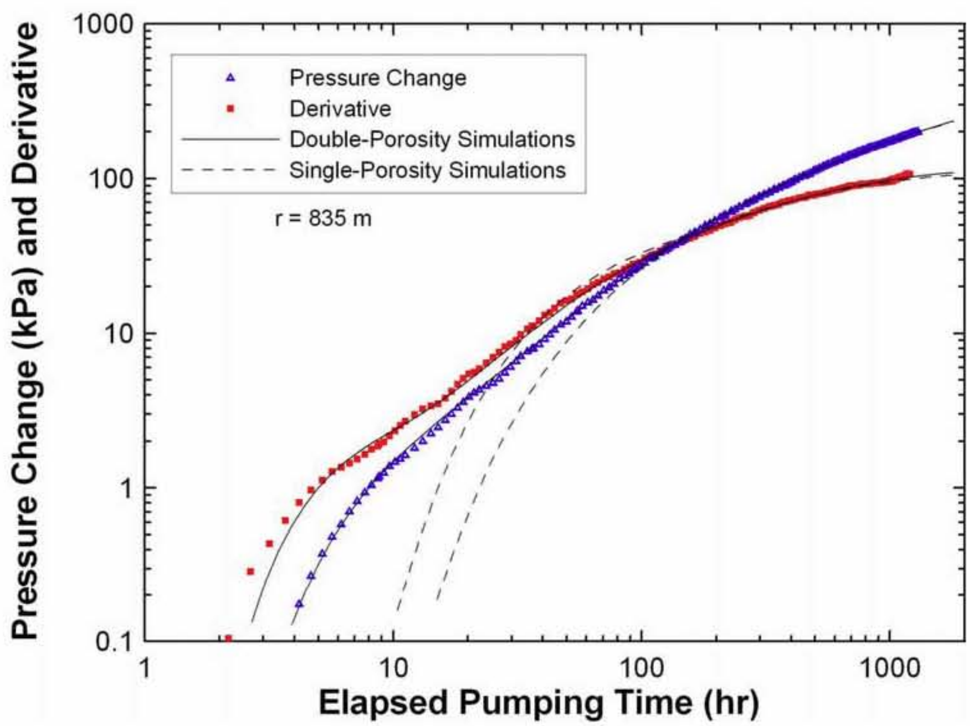

Figure 6. Double-porosity response observed at well H-3b2 to pumping 835 m away at well H-19b0.

When double-porosity behavior is observed, two diffusivities can be calculated from an observation-well response: the diffusivity of the fracture system and the diffusivity of the entire fracture+matrix system. For the response shown in Figure 5, for example, the fracture diffusivity is approximately 2.2 m^2/s, while the total system diffusivity is only 0.19 m^2/s. For the response shown in Figure 6, the fracture diffusivity is approximately 3.2 m^2/s, while the total system diffusivity is 0.71 m^2/s. In comparison, the diffusivity calculated for the Culebra at a low-T, unfractured location (the H-2 well pad) is only 0.04 m^2/s (Beauheim and Ruskauff, 1998).

The Culebra pumping tests that produced observable responses at wells over 100 m away were all performed at wells showing high T ($\geq 6 \times 10^{-6}$ m^2/s) and evidence of fracturing. (Indeed, lower T locations typically cannot sustain pumping rates greater than 1-2 L/min, which are insufficient to produce observable responses over great distances in the Culebra.) Thus, the pressure responses observed at distant wells all involve some amount of propagation through fractures before, perhaps, encountering unfractured dolomite. The problem then is to distinguish pressure transient propagation entirely through fractures from that which starts in fractures but ends in unfractured rock.

Diffusivity Analysis

The identification of areas that are, and are not, interconnected by fractures can be approached by compiling and comparing the diffusivities calculated for each pumping well-observation well pair available in the context of the other information we have about fracturing. Table 1 shows the $\log_{10}$ diffusivities (in m^2/s) calculated from the various observation-well responses (Beauheim, 1986; 1987a,b; 1989; 2002; Beauheim and Ruskauff, 1998) and Figure 7 shows the $\log_{10}$ diffusivities plotted against the $\log_{10}$ T values (in m^2/s) obtained from the single-well tests at the observation wells (Beauheim, 1986; 1987a,b,c; 1989; 2002; Beauheim and Ruskauff, 1998; Beauheim et al., 1991; Roberts, 2006). The data from the test conducted on unfractured Culebra at the H-2 well pad described above are included (as a circle) on Figure 7 for comparison. Two lines are also plotted on Figure 7: the horizontal line at $\log_{10}$ T = -5.22 separates the wells showing double-porosity hydraulic behavior from those showing single-porosity behavior, while the vertical line at $\log_{10}$ D = 0.20 bounds all the wells above the horizontal line. The significance of these lines will be discussed below.

Several things are evident from Figure 7. First, as would be expected, diffusivity tends to increase as the transmissivity at the observation well increases. But for a given T, there is also a fair amount of scatter, sometimes exceeding two orders of magnitude, in the corresponding value of D. If the Culebra was characterized by a single value of S, we would expect the data in Figure 7 to plot closely around a unit-slope line. The observed scatter may be caused by at least three factors. First, S varies by over an order of magnitude in the Culebra (Beauheim and Ruskauff, 1998), and by even more when fracture S is differentiated from matrix (or total system) S. Second, each calculated value of D reflects not just the T and S at the observation well, but also the T and S between the pumping well and the observation well (and even beyond the observation well; Oliver, 1993). Therefore, the D

Table 1. Summary of $\log_{10}$ D values calculated from observation-well responses.

Pumping Well	Observation Well	Well Separation (m)	$\log_{10}$ D (m^2/s)
DOE-2	*H-6b*	3100	2.3
	WIPP-13	1475	1.5
H-3b2	*DOE-1*	1610	1.0
	H-1	830	-1.7
	H-2b2	1280	-1.4
	H-11b1	2420	1.2
H-9c	*Engle*	1250	1.3
H-11b1	CB-1	2410	-0.67
	DOE-1	1210	0.61
	H-3b2	2420	1.3
	H-14	3245	-0.76
	H-15	2730	0.21
	H-17	1660	-0.11
	P-17	2190	-0.32
H-19b0	ERDA-9	1490	-0.52
	H-1	1460	-0.63
	H-3b2	835	0.50
	WQSP-5	920	-0.52
SNL-2	*H-6b*	2120	0.72
SNL-9	H-2b2	4000	-0.23
	H-6b	3350	1.1
	IMC-461	2525	1.1
	WIPP-25	2930	1.2
SNL-14	C-2737	3990	-0.05
	ERDA-9	4500	0.05
	H-3b2	3490	0.29
	H-4b	2720	0.13
	H-9c	9460	1.3
	H-11b4	1510	0.96
	H-12	3010	-0.32
	H-15	4220	0.50
	H-17	760	-0.52
	H-19b0	3090	0.55
	SNL-12	5230	1.9

Pumping Well	Observation Well	Well Separation (m)	$\log_{10}$ D (m^2/s)
SNL-18	*SNL-3*	3520	0.77
	WIPP-30	1830	-0.15
WIPP-11	*H-6b*	3520	1.1
	SNL-1	7820	1.2
	SNL-3	3460	1.0
	SNL-5	1990	0.53
	WIPP-12	2950	-0.07
	WIPP-13	2510	1.7
	WIPP-30	3230	0.32
	WQSP-1	3290	1.7
	WQSP-2	2500	1.6
	WQSP-3	3090	0.09
WIPP-13	*DOE-2*	1475	1.3
	ERDA-9	2520	-0.36
	H-1	2680	-0.78
	H-2b2	2600	-0.63
	H-6b	2190	1.4
	P-14	4220	0.74
	WIPP-12	1290	-0.63
	WIPP-18	1530	-0.21
	WIPP-19	1830	-0.19
	WIPP-21	2220	-0.35
	WIPP-22	1930	-0.36
	WIPP-25	6260	0.96
	WIPP-30	5560	0.73
WIPP-25	*IMC-461*	1800	1.1
WQSP-1	H-18	395	-0.19
	WIPP-13	820	0.49
WQSP-2	*DOE-2*	1320	0.70
	H-18	1710	0.40
	WIPP-13	1165	0.54
	WQSP-1	1330	0.70
P-14	D-268	3120	0.84
	H-6b	3390	1.1
	WIPP-25	3390	1.2

Italics denote high-T wells (i.e., known fracturing)
Shaded values denote fracture diffusivities calculated from double-porosity analyses

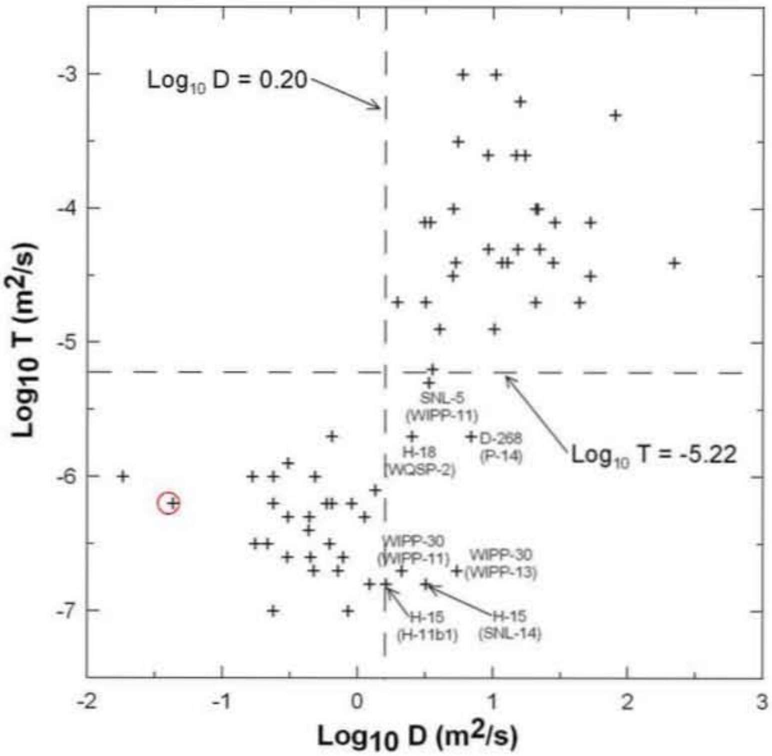

Figure 7. Log_{10} diffusivities calculated from observation-well responses versus log_{10} transmissivities from single-well tests at the observation wells. The circle shows the values obtained from a test of unfractured Culebra on the H-2 well pad. Labels on points give the observation well with associated pumping well in parentheses.

calculated for a given observation well may differ depending on what well was being pumped to produce the response. Third, some degree of uncertainty is associated with each D estimate, particularly for those derived from a double-porosity analysis. Double-porosity responses over distances of hundreds to thousands of meters may be subtle, and simply demonstrating that a double-porosity response is present may be easier than quantifying the values of the double-porosity parameters (storativity ratio and interporosity flow coefficient) precisely. Even where single-porosity behavior is observed, arriving at unique estimates of D is often problematic when the magnitude of the overall response being simulated is small, as it often is over the distances involved in these tests.

All that being said, one important thing we notice from Figure 7 is that all of the well pairs showing log_{10} D values of 1.0 or greater involve wells that we already know to have high T (log_{10} T > -5.22)and other evidence of fracturing. Thus, we feel safe in concluding that these wells are directly interconnected by fractures. At the other extreme, all well pairs showing log_{10} D values less than 0 involve an observation well that we know to have low T and no evidence of fracturing. From this, we conclude that these wells are not directly interconnected by fractures. The fractures associated with the pumping wells in these couplets are probably responsible for the D values being higher than that observed at the H-2 well pad, where both the pumping and observation wells were in unfractured Culebra.

The well pairs showing $\log_{10}$ D values between 0 and 1 require more detailed attention. Twenty-three well pairs, involving 19 different observation wells, fall in this category (Table 1). Eleven of the observation wells are high-T wells, while the other eight are low-T wells. The $\log_{10}$ D values for the well pairs involving the 11 high-T wells are all approximately 0.5 or greater, with the exception of the SNL-14 – H-3b2 well pair, which has a $\log_{10}$ D value of only 0.29. All of these $\log_{10}$ D values most likely reflect fracture interconnection, with H-3b2 being not as well connected (or more tortuously) to SNL-14 as it is to the much closer well H-19b0. Of the well pairs involving the eight low-T observation wells, the three lowest $\log_{10}$ D values (≤0.13) are associated with wells (H-4b, WQSP-3, and ERDA-9) lying in regions with no evidence of fracturing. Hence, these three wells are probably not directly interconnected to the associated pumping wells by fractures. Three of the other low-T wells (D-268, H-18, and SNL-5) have $\log_{10}$ D values of 0.40 or greater, and also have the T values closest to, but below, the 6×10^{-6} m^2/s ($\log_{10}$ -5.22) threshold at which we begin to observe double-porosity behavior (Beauheim et al., 1991; Roberts, 2006). These three wells may simply have minor fracturing that does not dominate their hydraulic responses enough to create clear double-porosity responses. In any event, they are probably connected to their associated pumping wells by fractures to some degree. The two remaining low-T wells (H-15 and WIPP-30), with $\log_{10}$ D values between 0.21 and 0.73, encountered little to no fracturing in the Culebra (Mercer and Snyder, 1990; Sandia Laboratories and USGS, 1980) but, as suggested by Beauheim (1989; 1987b), must be near to fractures to have responded to the pumping tests as they did. Hence, a $\log_{10}$ D value of approximately 0.20 appears to represent the cut-off between well pairs connected by fractures from those that are not.

The spatial pattern of estimated diffusivities is shown in Figure 8. A revised version of the line separating fractured from unfractured regions in Figure 3 now shows the separation between regions with $\log_{10}$ D values greater and less than 0.20. The regions containing high-T wells show $\log_{10}$ D values greater than 0.20, reflecting fracture interconnections. The high-T region in the southeastern part of the WIPP site clearly seems to be interconnected to high T's farther to the south. The swath of Culebra running roughly NE to SW across the WIPP site that encompasses only low-T wells generally shows $\log_{10}$ D values less than 0.20. Combining this information with the fact that no responses to pumping in a high-T well on one side of this swath have ever been observed in high-T wells on the other side of the swath, we infer that a continuous band of unfractured, low-T Culebra separates the high-T Culebra found in the northwestern part of the WIPP site from the high-T Culebra found in the southeastern part of the site.

In contrast, the continuity of the low-T region that includes WIPP-30 and SNL-5 north of the WIPP site is more questionable. These wells appear to show some degree of fracture interconnection to other wells, and may simply be situated in localized unfractured blocks within a region that is generally fractured. Simulations of the SNL-5 pumping test, in fact, indicated the presence of higher transmissivity a few hundred meters away (Roberts, 2006).

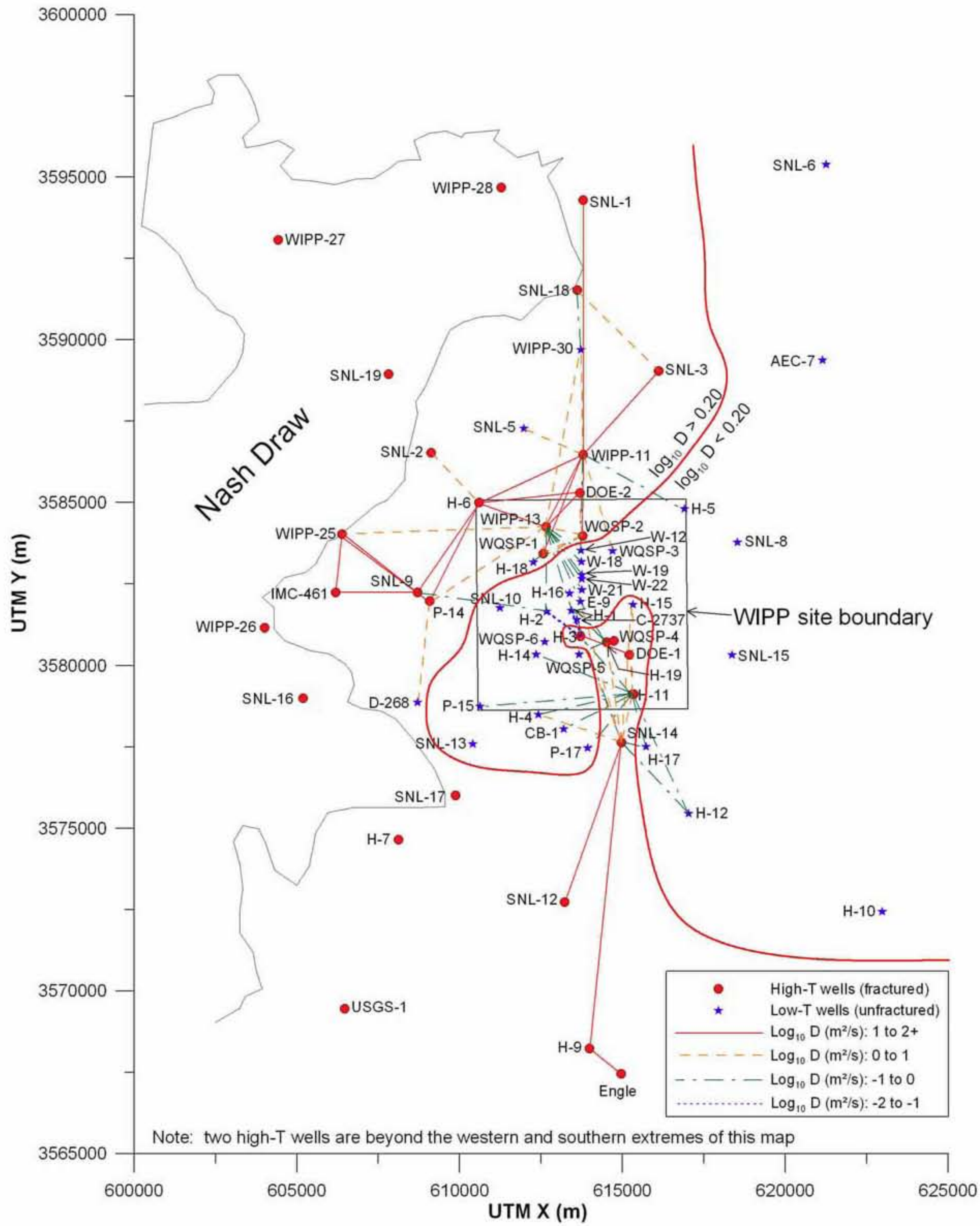

Figure 8. Log_{10} D values observed for pumping well-observation well pairs.

Summary and Conclusions

Hydraulic tests and other information from 66 Culebra well locations around the WIPP site have shown evidence of fracturing at 33 of the locations. With distances between fractured and unfractured well locations being as low as 0.4 km and many areas with neighboring wells greater than 1 km apart, however, the continuity of the fractured and unfractured zones cannot be ascertained from single-well data alone. Transport may be much higher in the fractured regions of the Culebra than in the nonfractured regions, hence a method is desired that allows us to determine where fractures are, and are not, present without having to continually drill and test wells.

Hydraulic diffusivity, the ratio of transmissivity and storativity, can be obtained from the analysis of observation-well responses to pumping tests in heterogeneous systems. Knudby and Carrera (2006) suggested that hydraulic diffusivity could be used as an indicator of connectivity between wells. We hypothesized that by combining inferred values of diffusivity with other information available on fracturing in the Culebra, we might be able to establish a threshold value of diffusivity above which fracture interconnectivity was present.

The results of this study suggest that the value of diffusivity obtained from analysis of an observation-well response to a pumping test can be used to determine if the pumping well and observation well are interconnected by fractures. For the Culebra dolomite at the WIPP site, a $\log_{10} D$ (m^2/s) value of approximately 0.2 or greater appears to distinguish wells that are interconnected by fractures from those that are not. Mapping the diffusivity values obtained from 69 observation-well responses during 15 pumping tests has allowed us to delineate a swath of the Culebra running from northeast to southwest across the WIPP site that appears to lack a network of interconnected fractures. All wells in this swath had already been tested and shown to have low transmissivity, but no conclusions could previously be drawn about the possible presence of nearby fractures.

In northwestern and southeastern portions of the WIPP site, in contrast, diffusivities are high and the Culebra appears to be well-connected to the north and west and to the south of the WIPP site, respectively, by fractures. A region to the north of the WIPP site that appeared to have low transmissivity and few fractures may be less extensive than previously thought, with localized blocks of unfractured Culebra surrounded by more generally fractured rock.

Diffusivity mapping may hold promise in other areas of intermittent fracturing as a means of identifying locations connected by fractures. The particular numeric threshold established for the Culebra dolomite at the WIPP site, however, is not likely to apply to a different rock at a different location. Diffusivities inferred from multiple pumping tests need to be combined with other information on fracturing to establish the appropriate threshold values for other sites.

Acknowledgements

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References

Beauheim, R.L., 1986, *Hydraulic-Test Interpretations for Well DOE-2 at the Waste Isolation Pilot Plant (WIPP) Site*, SAND86-1364, Albuquerque, NM: Sandia National Laboratories.

Beauheim, R.L., 1987a, *Analysis of Pumping Tests of the Culebra Dolomite Conducted at the H-3 Hydropad at the Waste Isolation Pilot Plant (WIPP) Site*, SAND86-2311, Albuquerque, NM: Sandia National Laboratories.

Beauheim, R.L., 1987b, *Interpretation of the WIPP-13 Multipad Pumping Test of the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site*, SAND87-2456, Albuquerque, NM: Sandia National Laboratories.

Beauheim, R.L., 1987c, *Interpretations of Single-Well Hydraulic Tests Conducted At and Near the Waste Isolation Pilot Plant (WIPP) Site, 1983-1987*, SAND87-0039, Albuquerque, NM: Sandia National Laboratories.

Beauheim, R.L., 1989, *Interpretation of H-11b4 Hydraulic Tests and the H-11 Multipad Pumping Test of the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site,* SAND89-0536, Albuquerque, NM: Sandia National Laboratories.

Beauheim, R.L., 2002, *Analysis Package for Interpretation of 1984 H-3 Pumping Tests*, ERMS# 522203, Carlsbad, NM: Sandia National Laboratories, WIPP Records Center.

Beauheim, R.L., and G.J. Ruskauff, 1998, *Analysis of Hydraulic Tests of the Culebra and Magenta Dolomites and Dewey Lake Redbeds Conducted at the Waste Isolation Pilot Plant Site*, SAND98-0049, Albuquerque, NM: Sandia National Laboratories.

Beauheim, R.L., T.F. Dale, and J.F. Pickens, 1991, *Interpretations of Single-Well Hydraulic Tests of the Rustler Formation Conducted in the Vicinity of the Waste Isolation Pilot Plant Site, 1988-1989*, SAND89-0869, Albuquerque, NM: Sandia National Laboratories.

Gringarten, A.C., 1984, "Interpretation of Tests in Fissured and Multilayered Reservoirs with Double-Porosity Behavior: Theory and Practice," *Journal of Petroleum Technology*, 36(4): 549-564.

Gringarten, A.C., 1987, "How to Recognize 'Double-Porosity' Systems from Well Tests," *Journal of Petroleum Technology*, 39(6): 631-633.

Holt, R.M., R.L. Beauheim, and D.W. Powers, 2005, "Predicting Fractured Zones in the Culebra Dolomite," *in* Dynamics of Fluids and Transport in Fractured Rock, *Geophysical Monograph Series 162*, American Geophysical Union, 103-115.

Knudby, C., and J. Carrera, 2006, "On the Use of Apparent Hydraulic Diffusivity as an Indicator of Connectivity," *Journal of Hydrology*, 329: 377-389.

Mercer, J.W., 1983, *Geohydrology of the Proposed Waste Isolation Pilot Plant Site, Los Medaños Area, Southeastern New Mexico*, Water-Resources Investigations Report 83-4016, Albuquerque, NM: U.S. Geological Survey.

Mercer, J.W., and R.P. Snyder, 1990, *Basic Data Report for Drillholes H-14 and H-15 (Waste Isolation Pilot Plant—WIPP)*, SAND89-0202, Albuquerque, NM: Sandia National Laboratories.

Oliver, D.S, 1993, "The Influence of Nonuniform Transmissivity and Storativity on Drawdown," *Water Resources Research*, 29(1): 169-178.

Roberts, R.M., 2006, *Analysis Report for AP-070, Analysis of Culebra Pumping Tests Performed Between December 2003 and August 2005,* ERMS# 539221, Carlsbad, NM: Sandia National Laboratories, WIPP Records Center.

Sandia Laboratories and United States Geological Survey, 1980, *Basic Data Report for Drillhole WIPP 30 (Waste Isolation Pilot Plant—WIPP)*, SAND79-0284, Albuquerque, NM: Sandia National Laboratories.

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