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**REGIONAL GEOTHERMAL EXPLORATION IN
NORTH CENTRAL NEW MEXICO**

Final Report

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6. NAME AND ADDRESS OF PERFORMING ORGANIZATION New Mexico State University Energy Institute Box 3EI, Las Cruces, NM 88003		
7. ABSTRACT A broad-based geothermal resource reconnaissance study covering Bernalillo, Los Alamos, Rio Arriba, San Miguel, Sandoval, Santa Fe, Taos, Torrance, and Valencia counties in north central New Mexico was conducted from June 15, 1981, through September 30, 1983. Specific activities included the compilation of actual temperature, bottom-hole temperature gradient, and geotemperature data; tabulation of water chemistry data; field collection of temperature-depth data from existing wells; and drilling of temperature gradient holes in the Ojo Caliente, San Ysidro, Rio Puerco, and Polvadera areas. The data collected were used to perform: (1) a regional analysis of the geothermal energy potential of north central New Mexico; (2) two site-specific studies of the potential relationship between groundwater constrictions and geothermal resources; (3) an evaluation of the geothermal energy potential at Santa Ana Pueblo; (4) a general analysis of the geothermal energy resources of the Rio Grande Rift, including specific data on the Valles Caldera; and (5) an evaluation of the use of geothermometers on New Mexico groundwaters.		
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Introduction

This report summarizes the work accomplished as part of a broad-based geothermal resource reconnaissance study covering Bernalillo, Los Alamos, Rio Arriba, San Miguel, Sandoval, Santa Fe, Taos, Torrance, and Valencia counties in north central New Mexico during the period June 15, 1981, through September 30, 1983. The research program was funded, in part, by the U.S. Department of Energy (Contract DE-AS07-78ID01717) and was administered by the New Mexico State University Energy Institute. Staff members of the Energy Institute, the New Mexico State University Department of Physics, and the Los Alamos National Laboratory conducted the research activities. Specific activities included the compilation of actual temperature, bottom-hole temperature gradient, and geotemperature data; tabulation of water chemistry data; field collection of temperature-depth data from existing wells; and drilling of temperature gradient holes in the Ojo Caliente, San Ysidro, Rio Puerco, and Polvadera areas. The data collected were used to perform: (1) a regional analysis of the geothermal energy potential of north central New Mexico; (2) two site-specific studies of the potential relationship between groundwater constrictions and geothermal resources; (3) an evaluation of the geothermal energy potential at Santa Ana Pueblo; (4) a general analysis of the geothermal energy resources of the Rio Grande Rift, including specific data on the Valles Caldera; and (5) an evaluation of the use of geothermometers on New Mexico groundwaters.

This report is divided into eight chapters. The summary analysis of the geothermal energy potential of north central New Mexico is given in Chapter 1. Measured geothermal gradients (Chapter 2), temperature

gradient studies near groundwater constrictions (Chapter 3), and geothermal resources of the Rio Grande Rift (Chapter 5) summarize specific aspects of the geothermal energy resource base in north central New Mexico. Some of the thermal and geochemical data compiled during the course of this study are reproduced in Chapters 4 and 6, respectively. The evaluation of geothermometers based on a wide range of groundwater samples is discussed in Chapter 7. Field data obtained from the temperature gradient hole drilling program are summarized in Chapter 8.

Many of the data presented in this report may be used to update the user-oriented geothermal resources map of New Mexico (Swanberg, 1980) and will appear as part of the scientific geothermal resources map of New Mexico series (Swanberg, 1983). The results of this north central New Mexico geothermal resource assessment activity hopefully provide a foundation on which site-specific geothermal exploration activities may be based, with the ultimate goal of accelerating the development of geothermal energy into a technically and economically viable energy resource to serve the industrial, commercial, and agricultural sectors in north central New Mexico.

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L. Icerman
Editor

1.0 Analysis of the Geothermal Energy Potential of North Central New Mexico*

1.1 Introduction

The study area (see Figure 1-1) is located in the north central part of New Mexico (see insert, Figure 1-1) and encompasses the state's largest population center (Albuquerque) and capitol (Santa Fe), plus a number of other significant population centers (e.g., Los Alamos, Socorro, Taos, Espanola, Belen, and Las Vegas). The elevation ranges from less than 5,000 feet on the floor of the Albuquerque-Belen Basin to over 13,000 feet at the top of the Sangre de Cristo Mountains. Climatologically, the study area ranges from arid desert to semi-arid mountain ranges. The annual precipitation ranges from approximately 10 inches in the desert valleys to over 35 inches in the mountain ranges.

The main physiographic features are two deep northerly trending inter-mountain basins (i.e., Albuquerque-Belen and Espanola) translated easterly by right echeloning of the bordering uplifts (Kelley, 1979) and flanked by the Manzano-Sangre de Cristo mountain ranges on the east, the Jemez-Magote Ridge mountain system to the northwest, and the Magdalena Mountains and the Sierra Lucero to the southwest. The entrenched Rio Grande runs N-S and NNE-SSW throughout the two late-Cenozoic sedimentary basins and flows in a southerly direction.

The geomorphic setting is one of elongated deep structural basins within adjacent mountain uplifts that trend in general N-S and NNE-SSW directions. The mountain uplifts range from faulted and rotated

* The principal author of Chapter 1 is Richard L. Lohse, Geothermal Field Engineer, New Mexico State University Energy Institute.

Figure 1-1. Location map for the area in north central New Mexico surveyed for geothermal energy potential.

Paleozoic blocks to intrusive and extrusive volcanic complexes in the major mountain ranges. There are also many smaller late-Cenozoic basaltic vents and associated lava flows throughout much of the study area. Tectonically, the study area encompasses the central segment of the Rio Grande Rift as defined by Chapin (1971) and modified by Kelley (1979) and Callender and Seager (1980). Reiter et al. (1978) have placed this part of the rift within a high heat flow envelope of greater than 2.5 HFU.

1.2 Temperature Data

1.2.1 Actual Temperature Data

The actual temperatures of wells and springs are shown in Figure 1-2. The data were compiled from USGS WATSTORE and GEOTHERM files, Swanberg (1980a, 1980b, 1980c), Berry et al. (1980), and Hunter (1983). In order to increase the size of the data base, all temperatures recorded from depths less than 150 meters were included in Figure 1-2. Data from depths greater than 150 meters were excluded so that areas shown to be anomalous in Figure 1-2 were not the result of normal temperature data from exceptionally deep wells.

Actual temperatures of a number of wells of unknown depth were also included in Figure 1-2. These actual temperatures were included to increase the total coverage and density of the data set and to better define the background and regional temperature variations. The validity of using these temperatures of unknown depth comes from the fact that most of the actual temperatures are relatively cold (i.e., $<22.5^{\circ}\text{C}$)

Figure 1-2. Actual temperatures (°C) of wells less than 150 m deep and of springs in north central New Mexico. Surface temperatures are reported for springs. Some of the wells are of unknown depth. The data are compiled from USGS WATSTORE and GEOTHERM files, Swanberg (1980a, 1980b, 1980c), Berry et al. (1980), and Hunter (1983).

indicating that these data correspond to shallow wells or represent anomalously cool parts of the crust when the temperatures come from deeper wells. In either case, these temperature data add to the knowledge of the thermal structure of the study area by filling in void spaces in the data set and by showing where the crust is not anomalously warm.

When the actual temperatures of unknown depth are anomalously warm, additional information may be gained by examining bottom-hole temperature gradient data (see Figure 1-3) in the vicinity of the anomalously warm actual temperatures. If the bottom-hole temperature gradients are elevated, then an anomalously warm crust is indicated and the warm actual temperatures are judged to be from relatively shallow depths. If, on the other hand, the bottom-hole temperature gradients are normal or low, then a normal or cool crust is indicated and the warm actual temperatures are probably from unusually deep wells. Therefore, by using the actual temperature data of unknown depth in conjunction with the bottom-hole temperature gradient data, additional information may be gained about the thermal structure of the study area and warming trends and patterns may be better defined.

Data from approximately 1,050 locations were screened for anomalous temperatures and analyzed for warming trends and patterns. Actual temperatures range from approximately 5 to 90°C, with 43 sites having temperatures greater than 30°C and 73 sites having temperatures between 22.5 and 30°C.

1.2.2 Bottom-Hole Temperature Gradients

Bottom-hole temperature gradients were calculated in order to identify areas within the crust which are characterized by elevated

Figure 1-3. Bottom-hole temperature gradients ($^{\circ}\text{C}/\text{km}$) of wells in north central New Mexico for an assumed surface temperature of 15°C . The data are compiled from the USGS GEOTHERM file, Swanberg (1980b), and Hunter (1983).

temperatures. The gradients were calculated using bottom-hole temperature and depth data and an assumed surface temperature of 15°C. No temperature data from depths less than 10 meters were used in order to avoid diurnal and annual temperature disturbances. Computed bottom-hole temperature gradients are shown in Figure 1-3 and tabulated in Table 1-1. The bottom-hole temperature and depth data used in calculating the bottom-hole temperature gradients were taken from the USGS GEOTHERM file, Swanberg (1980b), and Hunter (1983). Bottom-hole temperature gradients were calculated for approximately 550 sites, with 93 sites having gradients greater than 60°C/km and 22 sites having bottom-hole temperature gradients between 45 and 60°C/km.

1.2.3 Geotemperature Data

Geotemperature data were compiled from the USGS WATSTORE file and Swanberg (1980a, 1980c). Figures 1-4 and 1-5 show the SiO₂ and Na-K-Ca geotemperature data, respectively. Silica geotemperatures exist for approximately 200 sites, with approximately 50 sites indicating reservoir base temperatures over 90°C and about 85 sites having geotemperatures between 60 and 90°C. Alkali (Na-K-Ca) geotemperatures are available for approximately 160 sites, with about 25 sites indicating reservoir base temperatures in excess of 105°C and approximately 30 sites indicating reservoir base temperatures between 70 and 105°C.

1.2.4 Anomalous Temperature Data

Sites characterized by anomalous temperature data are shown in Figure 1-6. Actual temperatures greater than or equal to 22.5°C and bottom-hole temperature gradients greater than or equal to 45°C/km are considered anomalous within the study area. In general, the main area

Table 1-1. Computed bottom-hole temperature gradients for wells in north central New Mexico.

Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
34°00.6'	106°46.7'	20.0	184	27	2
34°00.6'	106°54.1'	21.5	56	115	2
34°00.7'	107°00.2'	23.0	47	169	2 (SEDILLO A)
34°01.0'	106°45.0'	20.0	87	57	2
34°01.4'	106°52.8'	12.5	27	-91	2
34°01.7'	106°53.4'	15.5	34	14	2
34°01.7'	106°51.6'	18.0	46	65	2
34°02.4'	106°48.8'	23.0	120	66	2 (PUEBLITO W)
34°02.4'	107°04.7'	22.0	165	42	2 (STROZZI W)
34°02.6'	106°53.4'	15.4	30	13	2
34°02.6'	106°54.5'	18.5	40	88	2
34°02.6'	106°54.5'	21.0	69	87	2
32°02.6'	106°55.0'	19.0	91	43	2
34°02.7'	106°57.2'	32.4	91	190	2
34°02.8'	106°54.7'	23.0	40	201	2
34°02.8'	106°53.6'	20.0	23	221	2
34°02.9'	106°55.2'	18.0	43	70	2
34°03.0'	106°53.4'	21.0	16	378	2
34°03.2'	106°53.7'	18.0	36	84	2
34°03.3'	106°53.8'	20.0	27	188	2
34°03.4'	106°54.9'	18.5	20	173	2
34°03.5'	106°55.0'	18.5	35	99	2
34°03.6'	106°55.0'	18.0	35	85	2
34°03.6'	106°55.2'	18.0	34	87	2
34°03.8'	107°25.9'	21.0	89	67	2 (DIVICE WE)
34°03.9'	106°55.0'	19.0	36	111	2
34°03.9'	106°55.4'	20.7	56	101	2
34°04.0'	106°54.7'	18.0	37	82	2
34°04.0'	106°55.2'	17.0	21	93	2
34°04.0'	106°57.0'	43.0	61	459	2
34°04.3'	106°54.5'	23.0	21	374	2
34°04.3'	106°54.5'	16.9	30	62	2
34°04.3'	106°55.0'	18.0	31	97	2
34°04.5'	106°54.6'	18.0	15	196	2
34°04.6'	106°52.6'	18.5	15	229	2
34°04.8'	106°54.5'	19.0	19	208	2
34°05.0'	106°39.0'	14.5	96	5	2 (BUSTOS W)
34°05.0'	106°53.7'	22.0	26	270	2
34°05.1'	106°53.7'	19.0	18	218	2
34°05.3'	107°02.0'	18.0	41	73	2
34°05.4'	106°53.9'	16.0	29	34	2

Table 1-1. (Continued).

Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
34°05.4'	106°54.0'	22.0	27	255	2
34°05.5'	106°54.1'	20.0	24	205	2
34°05.5'	106°53.9'	14.5	33	-15	2
34°05.6'	106°54.0'	20.0	32	156	2
34°05.7'	106°54.5'	18.8	61	62	2
34°05.8'	106°53.5'	18.0	13	234	2
34°05.9'	106°54.5'	19.0	55	72	2
34°06.0'	106°54.2'	19.0	34	119	2
34°06.0'	107°14.0'	18.0	55	54	2 (BLOMQUIST)
34°06.0'	106°53.8'	19.0	12	328	2
34°06.1'	107°13.9'	18.0	73	41	2 (PRICKETT)
34°06.5'	107°06.7'	19.0	85	46	2
34°06.7'	107°08.1'	22.0	128	54	2
34°06.8'	106°53.8'	20.0	16	315	2
34°07.0'	105°40.1'	13.5	120	-12	2
34°07.1'	106°53.4'	18.0	10	298	2
34°07.5'	106°56.0'	23.0	77	103	2
34°07.6'	107°08.2'	21.0	96	62	2
34°08.1'	106°54.2'	17.0	12	164	2
34°08.2'	106°54.1'	17.0	44	45	2
34°08.4'	106°54.0'	15.5	32	15	2
34°08.5'	107°05.5'	19.0	46	87	2
34°08.6'	105°39.4'	14.5	111	-4	2
34°08.6'	107°11.4'	20.0	99	50	2
34°08.7'	107°12.7'	17.0	48	41	2
34°09.1'	106°54.1'	15.0	15	0	2
34°09.3'	106°54.9'	17.0	27	75	2
34°09.3'	106°55.1'	21.0	43	140	2
34°09.4'	106°55.5'	16.0	64	15	2 (LEWARK WE)
34°09.5'	106°54.2'	19.0	27	145	2
34°09.5'	106°54.6'	15.5	15	32	2
34°09.5'	106°54.9'	18.0	24	123	2
34°09.8'	107°06.3'	22.0	49	143	2
34°10.4'	107°11.4'	19.0	119	33	2
34°10.7'	106°55.3'	20.0	49	102	2
34°10.9'	106°54.9'	19.0	40	100	2
34°11.3'	106°55.6'	18.0	24	123	2
34°11.4'	106°55.3'	19.0	18	218	2
34°11.4'	106°55.5'	9.0	30	-196	2
34°11.8'	106°55.3'	17.0	11	187	2
34°11.8'	106°54.5'	18.0	38	78	2
34°12.0'	107°05.4'	18.0	85	35	2
34°12.2'	106°55.2'	18.0	16	182	2

Table 1-1. (Continued).

Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
34°12.3'	106°49.0'	17.0	14	145	2
34°12.3'	106°54.5'	16.5	30	49	2
34°12.4'	106°55.9'	21.0	54	111	2
34°12.7'	106°54.8'	21.0	23	262	2
34°12.7'	106°56.0'	20.0	30	164	2
34°12.9'	106°54.9'	20.0	12	431	2
34°13.1'	106°55.1'	20.0	11	468	2
34°17.5'	107°12.1'	22.5	58	129	2
34°20.7'	105°39.0'	17.7	209	12	2
34°24.4'	107°39.4'	21.0	1,402	4	2
34°26.1'	106°46.3'	22.5	41	182	2
34°26.8'	106°43.0'	17.5	98	25	2
34°27.3'	106°31.3'	15.5	59	8	2
34°27.6'	106°43.5'	17.0	116	17	2
34°28.0'	106°57.4'	19.0	123	32	2
34°28.4'	105°24.0'	16.5	91	16	2
34°29.0'	106°38.0'	19.0	122	32	2
34°30.0'	107°39.4'	16.0	41	24	2 (WATSON WE)
34°31.7'	107°34.4'	12.0	22	-138	2
34°32.3'	106°40.8'	23.0	57	140	2
34°32.5'	106°57.0'	20.5	79	69	2
34°32.8'	106°03.7'	15.0	67	0	2
34°33.1'	107°38.3'	16.0	78	12	2
34°33.5'	106°44.9'	13.5	12	-129	2
34°33.5'	106°10.4'	16.0	89	11	2
34°34.3'	106°03.2'	15.0	74	0	2
34°34.5'	106°42.8'	23.5	134	63	2
34°34.6'	106°03.6'	15.5	69	7	2
34°34.7'	106°39.5'	24.9	113	87	2
34°34.7'	106°55.7'	21.0	82	73	2
34°35.4'	107°35.4'	17.0	59	33	2 (SCHOOL HO)
34°35.6'	107°37.1'	18.5	91	38	2 (NO. 7 WIND)
34°35.6'	107°00.9'	18.5	134	26	3 (COMANCHE)
34°35.6'	106°02.0'	15.0	12	0	3
34°35.9'	105°52.2'	13.0	30	-65	3
34°36.0'	106°03.4'	13.5	37	-41	3
34°36.8'	106°57.5'	22.0	126	55	3
34°37.1'	107°30.1'	21.0	47	127	3 (ORO WM)
34°37.3'	106°50.9'	22.0	120	58	3
34°38.0'	107°20.3'	19.0	190	21	3
34°38.5'	106°11.0'	11.0	27	-145	3
34°38.6'	107°02.7'	21.5	189	34	3

Table 1-1. (Continued).

Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
34°38.7'	106°47.1'	20.5	158	34	3
34°39.2'	105°50.1'	15.0	37	0	3
34°39.3'	106°08.8'	14.0	50	-19	3
34°39.5'	106°08.7'	13.5	30	-49	3
34°39.5'	106°05.9'	14.5	46	-10	3
34°39.7'	106°05.6'	10.0	45	-110	3
34°39.7'	106°54.9'	18.0	30	99	3 (POPALITO)
34°40.0'	107°21.5'	18.0	61	49	3
34°40.2'	106°07.8'	14.0	60	-16	3
34°40.3'	107°21.3'	14.5	61	-8	3
34°40.5'	107°08.6'	15.5	24	20	3
34°40.7'	106°07.5'	10.0	30	-164	3
34°40.8'	106°31.6'	19.0	76	52	3
34°40.9'	106°07.4'	13.0	36	-55	3
34°41.2'	106°04.6'	14.0	62	-16	3
34°41.4'	107°16.9'	19.0	192	20	3 (V2 RANCH)
34°41.5'	106°30.8'	11.0	13	-312	3
34°41.7'	106°50.4'	20.7	169	33	3 (J MAES WL)
34°42.4'	106°07.8'	13.0	61	-32	3
34°42.5'	106°07.1'	15.0	26	0	3
34°43.1'	106°58.3'	18.8	173	21	3 (SHELL WELL)
34°43.7'	106°00.7'	13.0	12	-172	3
34°44.8'	106°59.8'	18.0	41	74	3
34°45.0'	106°05.5'	14.5	55	-9	3
34°45.3'	106°04.2'	13.5	46	-32	3
34°45.4'	106°16.9'	19.0	61	65	3
34°45.4'	106°11.2'	12.0	81	-37	3
34°45.7'	106°03.8'	15.5	21	24	3
34°45.8'	106°39.5'	20.7	90	63	3
34°46.3'	106°06.2'	15.0	83	0	3
34°46.6'	106°04.8'	15.5	69	7	3
34°46.9'	106°06.4'	13.5	68	-21	3
34°47.7'	106°05.6'	14.5	39	-12	3
34°47.7'	106°02.8'	14.5	88	-5	3
34°48.0'	106°42.9'	15.5	18	28	3
34°48.2'	105°55.7'	13.5	83	-18	3
34°48.3'	106°44.0'	18.5	50	69	3
34°48.3'	106°43.8'	18.0	122	24	3
34°48.5'	106°34.3'	23.0	200	40	3
34°48.5'	106°42.3'	15.0	24	0	3
34°48.6'	106°04.4'	13.5	98	-15	3
34°48.7'	106°55.1'	16.2	176	6	3

Table 1-1. (Continued).

Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
34°48.7'	106°07.7'	11.0	52	-77	3
34°48.8'	106°03.0'	14.0	91	-10	3
34°48.8'	106°44.4'	19.5	185	24	3
34°50.1'	106°06.2'	14.5	71	-7	3
34°51.2'	106°46.6'	29.0	4,968	2	3
34°51.4'	106°03.0'	13.5	27	-54	3
34°52.0'	106°00.8'	13.0	76	-26	3
34°52.5'	106°59.2'	18.0	30	101	3
34°53.5'	106°02.5'	15.5	105	4	3
34°54.3'	106°02.9'	15.0	57	0	3
34°54.5'	106°54.1'	21.5	209	31	3
34°56.2'	106°02.5'	15.0	85	0	3
34°56.7'	106°03.4'	13.5	38	-39	3
34°56.9'	106°46.5'	20.0	131	38	3
34°56.9'	106°41.3'	14.0	23	-46	3
34°57.6'	106°41.7'	15.5	11	46	3 (PAJARGRNT)
34°57.7'	106°00.7'	14.5	23	-22	3
34°57.9'	107°30.8'	14.5	12	-40	3
34°58.0'	106°05.0'	15.0	76	0	3
34°58.0'	106°29.1'	16.5	23	64	3
34°58.1'	106°42.5'	16.0	35	28	3 (PAJARGRNT)
34°58.1'	106°04.2'	14.0	94	-10	3
34°58.1'	106°16.6'	15.5	49	10	3
34°58.1'	106°03.4'	14.5	92	-5	3
34°59.0'	106°16.3'	10.5	22	-202	3
34°59.4'	107°10.3'	21.5	76	85	3
34°59.5'	106°40.0'	19.0	22	182	3
35°00.0'	106°39.7'	21.0	29	207	3
35°00.1'	106°03.0'	15.0	55	0	3
35°00.5'	106°58.0'	58.0	1,105	38	2
35°00.8'	106°15.4'	13.0	57	-35	2
35°01.1'	107°16.6'	31.5	524	31	2
35°01.5'	106°35.3'	19.5	104	43	2
35°01.5'	106°41.7'	16.5	10	149	2 (ATISGRNT)
35°01.5'	106°38.3'	25.0	274	36	2
35°01.7'	106°41.7'	16.5	14	109	2 (ATISCOGR)
35°01.7'	106°41.8'	15.5	13	39	2 (ATISGRNT)
34°01.9'	106°43.1'	20.0	43	117	2 (ATISGRNT)
35°02.0'	106°56.3'	15.5	46	10	2 (ATISGRNT)
35°02.2'	106°38.6'	20.5	28	196	2
35°02.2'	106°43.5'	28.5	427	31	2
35°02.3'	105°59.1'	12.0	20	-149	2

Table 1-1. (Continued).

Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
35°02.4'	106°28.4'	15.5	22	22	2
35°02.5'	105°54.4'	14.0	48	-20	2
35°02.5'	106°03.9'	15.0	57	0	2
35°02.7'	106°03.0'	14.5	76	-6	2
35°02.7'	107°30.3'	20.0	44	113	2
35°02.8'	107°26.5'	16.0	38	26	2
35°02.8'	107°26.4'	16.0	37	26	2
35°02.8'	106°03.8'	14.0	82	-12	2
35°02.9'	107°26.8'	16.0	38	26	2
35°02.9'	107°36.7'	14.5	44	-11	2
35°03.0'	106°26.5'	16.0	15	65	2 (R MCDAN)
35°03.0'	106°26.5'	16.0	18	54	2 (R MCDAN)
35°03.0'	107°31.7'	15.5	47	10	2 (76-2 WELL)
35°03.0'	107°26.5'	16.0	37	27	2
35°03.1'	105°59.5'	14.0	61	-16	2
35°03.2'	107°26.6'	15.0	37	0	2
35°03.2'	106°34.9'	20.0	304	16	2
35°03.2'	106°35.3'	16.5	300	5	2
35°03.2'	106°39.7'	14.5	12	-41	2 (ALBUQGRNT)
35°03.2'	107°37.1'	15.5	131	3	2
35°03.2'	106°30.1'	14.3	366	-1	2
35°03.3'	106°03.9'	15.0	58	0	2
35°03.3'	105°43.8'	14.5	34	-14	2
35°03.4'	107°33.1'	15.5	40	12	2
35°03.4'	105°56.7'	15.0	40	0	2
35°03.5'	106°40.9'	16.5	11	136	2 (ATSCGRNT)
35°03.5'	106°40.9'	15.5	11	44	2 (BATISGRNT)
35°03.5'	107°03.6'	20.5	41	133	2
35°03.6'	106°22.8'	11.5	29	-119	2
35°03.7'	106°02.9'	14.0	82	-12	2
35°03.7'	106°59.8'	20.5	59	93	2
35°03.9'	106°27.5'	17.0	28	72	2
35°03.9'	106°39.2'	13.5	12	-123	2 (ALBUQGRNT)
35°03.9'	106°16.4'	13.5	100	-14	2
35°04.0'	107°05.7'	23.5	20	429	2
35°04.1'	107°05.6'	23.5	20	429	2
35°04.1'	106°11.1'	15.5	100	5	2
35°04.1'	106°30.3'	15.5	366	1	2
35°04.1'	106°31.0'	25.0	518	19	2 (LOMAS NO.8)
35°04.2'	105°59.8'	13.5	29	-51	2
35°04.2'	107°35.6'	13.5	72	-20	2
35°04.3'	106°41.3'	32.0	387	43	2

Table 1-1. (Continued).

Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
35°04.3'	106°44.4'	31.0	360	44	2 (ATISCOGRNT)
35°04.3'	105°59.2'	13.0	92	-21	2
35°04.3'	106°52.1'	25.5	411	25	2 (BATISCOGRNT)
35°04.3'	106°31.4'	26.5	512	22	2 (LOMAS 7)
35°04.4'	106°30.4'	23.3	408	20	2
35°04.5'	106°30.4'	23.5	408	20	2
35°04.5'	105°53.0'	15.0	94	0	2
35°04.6'	107°05.7'	20.0	131	38	2
35°04.7'	106°43.9'	34.5	372	52	2
35°04.7'	106°43.2'	40.5	363	70	2
35°04.9'	106°44.3'	31.1	360	44	2
35°05.0'	106°01.4'	13.5	43	-35	2
35°05.0'	106°39.4'	18.5	11	328	2 (ALBUQ GRNT)
35°05.0'	106°44.3'	31.0	360	44	2
35°05.0'	106°57.2'	21.5	62	104	2
35°05.1'	105°57.9'	13.5	27	-54	2
35°05.1'	106°40.4'	14.0	30	-32	2 (ALBUQ GRNT)
35°05.1'	106°32.9'	21.5	390	16	2
35°05.3'	106°39.1'	18.0	198	18	2 (ALBUQ GRNT)
35°05.3'	106°15.7'	13/0	79	-25	2
35°05.4'	106°22.5'	13.5	52	-28	2
35°05.4'	106°59.4'	18.0	84	35	2
35°05.4'	106°30.6'	24.5	549	17	2
35°05.6'	106°31.1'	25.0	430	23	2
35°05.7'	107°05.7'	19.0	174	23	2
35°05.9'	107°05.5'	18.5	226	15	2
35°05.9'	106°11.5'	14.5	104	-4	2
35°06.0'	106°41.9'	16.0	49	20	2 (ATISCOGRNT)
35°06.1'	106°32.2'	24.0	451	19	2
35°06.2'	106°44.1'	30.0	482	31	2 (ABQ COL 2)
35°06.3'	107°00.9'	18.5	39	89	2
35°06.4'	106°40.8'	21.0	305	19	2
35°06.6'	106°39.6'	16.0	21	48	2 (ALBUQ GRNT)
35°06.7'	106°21.4'	14.5	43	-11	2
35°06.7'	106°44.5'	28.0	512	25	2 (ABQ COL 1)
35°06.9'	106°22.4'	12.0	13	-234	2
35°06.9'	107°06.3'	21.0	60	100	2
35°07.1'	106°20.4'	16.0	49	20	2
35°07.4'	106°21.9'	12.0	56	-53	2
35°07.4'	106°42.5'	26.0	442	24	2 (ABQ COL 3)
35°07.5'	106°19.5'	13.0	94	-21	2
35°07.6'	106°00.8'	14.5	99	-5	2

Table 1-1. (Continued).

Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
35°07.6'	106°30.0'	24.5	89	104	2
35°07.7'	106°31.1'	24.0	402	22	2
35°07.7'	106°32.5'	23.5	372	22	2
35°07.8'	106°31.1'	23.9	405	21	2
35°07.8'	106°32.9'	22.8	332	23	2
35°07.9'	106°33.3'	23.0	332	24	2
35°08.0'	106°31.7'	25.5	482	21	2
35°08.0'	106°36.2'	17.2	317	6	2
35°08.1'	106°36.1'	17.0	317	6	2 (EL.GA.GRNT)
35°08.1'	106°14.9'	16.0	305	3	2
35°08.2'	106°33.3'	22.0	366	19	2 (EL.GA.GRNT)
35°08.2'	106°37.8'	14.5	21	-23	2 (EL.GA.GRNT)
35°08.4'	107°09.0'	20.5	47	116	2
35°08.4'	106°36.9'	16.5	46	32	2 (EL.GA.GRNT)
35°08.5'	107°23.1'	19.0	142	28	2
35°08.5'	106°31.7'	26.0	469	23	2
35°08.6'	107°05.9'	18.0	98	30	2
35°08.8'	105°58.9'	16.0	64	15	2
35°08.8'	106°32.3'	28.0	512	25	2
35°08.8'	106°35.7'	16.0	92	10	2 (EL.GA.GRNT)
35°08.8'	106°39.7'	14.5	34	-14	2 (EL.GA.GRNT)
35°08.9'	106°38.7'	14.5	17	-29	2 (EL.GA.GRNT)
35°08.9'	106°38.7'	15.5	12	41	2 (EL.GA.GRNT)
35°09.0'	107°24.0'	19.0	142	28	2
35°09.1'	106°09.4'	17.0	91	21	2
35°09.3'	106°38.2'	14.5	14	-36	2 (EL.GA.GRNT)
35°09.4'	106°56.3'	13.0	29	-68	1
35°09.5'	106°39.3'	15.0	13	0	1 (EL.GA.GRNT)
35°09.6'	106°20.0'	14.5	41	-12	1
35°09.7'	106°39.3'	15.0	14	0	1 (EL.GA.GRNT)
35°09.7'	106°42.7'	20.0	73	68	1
35°09.7'	106°12.0'	15.0	49	0	1
35°09.8'	106°21.1'	10.5	60	-74	1
35°09.9'	106°21.7'	13.0	60	-33	1
35°10.0'	106°39.0'	15.0	20	0	1 (EL.GA.GRNT)
35°10.3'	106°32.2'	29.0	546	25	1 (WALKER 2)
35°10.4'	106°32.6'	27.0	548	21	1 (WALKER 1)
35°10.4'	106°36.0'	14.5	91	-5	1 (EL.GA.GRNT)
35°10.5'	106°31.7'	20.5	229	24	1 (EL.GA.GRNT)
35°10.5'	105°53.3'	14.5	43	-11	1
35°11.4'	106°36.3'	14.5	49	-10	1
35°11.5'	106°38.2'	14.0	30	-32	1 (ALMEDAGRNT)

Table 1-1. (Continued).

Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
35°12.1'	107°08.7'	24.0	335	26	1
35°13.0'	106°42.7'	23.0	415	19	1 (N.M.UTIL)
35°13.6'	105°52.0'	16.0	122	8	1
35°14.0'	106°22.1'	12.0	87	-34	1
35°14.1'	105°47.6'	12.0	189	-15	1
35°14.7'	106°36.2'	15.0	21	0	1
35°15.6'	106°49.0'	21.5	305	21	1
35°15.9'	106°31.9'	20.0	107	46	1
35°16.4'	106°55.0'	20.0	37	136	1
35°18.0'	106°33.0'	16.5	31	48	3 (SAP/GP)
35°18.1'	106°33.4'	18.0	152	19	1
35°18.5'	106°04.8'	13.0	38	-52	1
35°18.8'	107°18.2'	14.5	76	-6	1
35°19.7'	106°33.3'	12.0	27	-109	1
35°20.0'	106°32.0'	17.6	34	77	3 (SAP/LV)
35°20.0'	107°38.8'	14.0	102	-9	1
35°20.0'	107°38.5'	13.5	61	-24	1
35°21.4'	106°56.7'	16/0	15	65	1
35°21.5'	106°18.8'	14.5	43	-11	1
35°22.6'	107°24.6'	13.0	114	-17	1
35°23.1'	106°27.9'	26.0	168	65	1 (ALGODONES)
35°23.3'	106°36.5'	16.0	56	17	1
35°23.7'	105°56.7'	13.5	27	-54	1
35°23.7'	106°25.2'	18.5	50	69	1
35°24.0'	106°09.4'	15.5	41	12	1
35°24.0'	106°34.0'	13.1	23	-83	3 (SAP/JD1)
35°24.0'	106°34.0'	15.7	120	6	3 (SAP/JD2)
35°24.5'	105°55.9'	14.8	77	-2	1
35°26.2'	106°39.9'	16.5	40	37	1
35°26.2'	107°32.0'	14.5	110	-4	1
35°28.0'	106°03.8'	17.0	35	57	1
35°28.1'	106°45.3'	14.5	40	-12	1
35°30.5'	106°47.7'	16.0	36	28	1
35°30.6'	107°30.1'	18.5	305	11	1
35°30.8'	107°27.8'	16.0	61	16	1
35°31.4'	107°30.1'	19.0	305	13	1
35°31.9'	107°31.8'	15.5	183	2	1
35°32.4'	106°08.1'	12.5	83	-30	1
35°32.6'	106°34.4'	23.5	338	25	1
35°32.9'	105°49.4'	14.5	19	-26	1 (CAVIDSO)
35°33.8'	105°44.6'	11.5	56	-62	1
35°34.1'	106°07.1'	15.0	50	0	1

Table 1-1. (Continued).

Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
35°34.2'	107°35.9'	14.5	137	-3	1
35°34.5'	107°12.3'	17.5	183	13	1 (HOMESTAK)
35°34.9'	105°46.1'	11.5	81	-43	1
35°35.3'	105°55.2'	13.5	91	-16	1
35°35.3'	105°46.2'	14.5	267	-1	1
35°35.7'	106°03.1'	17.0	69	29	1
35°35.9'	107°24.1'	24.5	381	24	1
35°35.9'	107°24.1'	24.5	381	24	1
35°36.6'	107°17.4'	16.0	74	13	1 (NMBM R21)
35°37.2'	107°31.3'	13.5	100	-15	1
35°38.0'	106°51.0'	46.0	168	184	2
34°38.4'	105°56.2'	14.0	91	-10	1
35°38.6'	106°53.4'	32.0	168	101	1
35°38.6'	106°53.4'	54.4	613	64	1
35°38.7'	106°02.8'	14.0	116	-8	1
35°39.5'	106°00.6'	13.5	34	-44	1
35°40.3'	106°02.6'	16.0	134	7	1
35°40.5'	106°53.0'	52.0	612	60	2
35°40.6'	105°58.2'	24.0	226	39	1 (SNTFEGRANT)
35°41.0'	105°57.7'	11.5	106	-33	1 (SNTFEGRANT)
35°43.0'	105°53.0'	14.5	171	-2	1
35°46.0'	106°09.2'	26.6	390	30	3 (CAJA #4)
35°46.0'	107°14.0'	32.0	366	46	2
35°47.0'	107°14.5'	68.0	1,408	37	2
35°49.0'	106°35.0'	12.9	31	-68	3 (PONDEROSA)
35°49.2'	106°08.6'	22.0	305	22	1
35°49.8'	106°38.9'	14.5	47	-10	1
35°50.0'	107°25.0'	83.0	1,584	42	2
35°50.1'	106°09.5'	23.5	332	25	1 (BUCKMAN)
35°51.5'	106°13.5'	28.0	762	17	1
35°52.0'	106°11.5'	23.0	600	13	1
35°52.2'	106°13.0'	20.5	196	28	1
35°52.2'	106°54.9'	16.3	847	1	1 (LA VENTA)
35°52.3'	106°11.0'	16.5	533	2	1
35°52.4'	106°15.5'	19.5	248	18	1
35°52.5'	106°37.5'	27.5	47	266	3 (LA CUEVA)
35°52.5'	106°42.0'	48.0	3,066	10	2
35°52.6'	106°10.4'	29.0	619	22	1
35°52.8'	106°59.5'	19.0	282	14	3 (LV/IM4)
35°53.0'	106°02.0'	14.6	56	-7	3 (POJAQUE)
35°53.0'	106°09.7'	14.5	265	-1	1
35°53.0'	106°40.0'	34.0	170	111	2

Table I-1. (Continued).

Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
35°53.0'	106°40.5'	195.0	2,900	62	2
35°53.0'	106°57.5'	14.5	122	-4	3 (LV/IM3)
35°53.0'	107°16.0'	32.0	304	55	2
35°53.0'	107°25.0'	48.0	686	48	2
35°53.4'	106°02.8'	11.0	24	-164	1
35°53.5'	106°05.0'	6.5	19	-442	1
35°53.6'	106°06.6'	13.5	21	-70	1
35°53.6'	106°59.5'	17.4	210	11	3 (LV/IM5)
35°53.7'	106°57.4'	17.0	204	9	1 (BRANDY 1)
35°53.8'	107°24.7'	15.5	18	27	1 (DHOE1 COA)
35°54.0'	106°40.0'	96.0	730	110	2
35°54.0'	107°22.7'	14.0	71	-14	1 (DHOE2 PCC)
35°54.1'	106°11.7'	25.5	610	17	1
35°54.1'	106°07.6'	13.5	12	-123	1
35°54.2'	106°11.9'	27.0	463	25	1
35°54.2'	107°25.4'	12.5	241	-10	1 (CCK-23)
35°54.3'	106°12.1'	25.0	607	16	1
35°54.5'	106°12.7'	28.0	549	23	1
35°54.5'	106°59.6'	22.0	348	20	3 (LV/IM6)
35°54.6'	106°13.2'	24.0	588	15	1
35°54.6'	107°22.0'	21.5	42	155	1 (19R-302)
35°54.7'	107°20.8'	12.0	16	-182	1 (DHOE4 COA)
35°54.7'	107°22.7'	16.0	55	18	1 (DHOE5 OB)
35°54.8'	106°13.6'	25.5	561	18	1
35°55.5'	107°27.8'	26.5	448	25	1
35°56.0'	106°40.0'	36.0	160	131	2
35°57.0'	106°10.0'	14.3	39	-18	3 (JACONITA)
35°57.2'	107°05.3'	13.0	91	-21	1
35°57.3'	106°05.2'	11.0	14	-291	1
35°57.4'	106°14.4'	23.3	290	29	3 (GARCIA #1)
35°57.9'	107°04.4'	14.5	73	-6	1
35°58.0'	105°54.0'	11.9	45	-69	3 (CUNDAYO)
35°58.0'	106°38.0'	45.0	210	142	2
35°58.1'	107°04.4'	14.5	73	-6	1
35°58.6'	106°59.0'	16.0	79	12	1 (BRANDY 2 B)
35°59.3'	106°03.0'	13.0	30	-65	1
35°59.4'	106°00.1'	12.0	46	-65	1
35°59.9'	105°55.8'	10.0	19	-260	1
35°59.9'	106°04.4'	13.5	46	-32	1
36°00.2'	107°22.6'	33.0	745	24	1 (STAR LK N)
36°01.1'	106°56.7'	12.0	45	-66	1
36°01.2'	106°57.9'	5.5	26	-362	1

Table 1-1. (Continued).

Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
36°01.2'	107°38.1'	10.0	290	-17	1
36°01.3'	106°56.9'	13.5	45	-33	1
36°01.3'	106°57.5'	5.5	30	-311	1
36°01.4'	106°57.6'	11.0	32	-126	1
36°01.5'	106°57.5'	11.0	32	-126	1
36°02.0'	106°57.9'	11.0	26	-154	1
36°02.5'	106°14.0'	23.5	290	29	3 (KHALSA)
36°02.9'	106°55.9'	13.5	61	-24	1
36°02.9'	106°55.8'	13.5	91	-16	1
36°04.2'	106°57.8'	13.5	51	-29	1
36°04.4'	106°57.8'	13.5	51	-29	1
36°05.0'	107°35.0'	63.0	1,356	35	2
36°07.5'	107°20.5'	9.5	55	-100	1
36°07.7'	107°21.0'	9.5	64	-85	1
36°08.9'	107°09.8'	12.0	61	-49	1
36°09.1'	107°10.0'	12.0	55	-54	1
36°10.0'	106°14.0'	10.4	35	-131	3 (PENASCO)
36°10.5'	107°15.5'	43.0	732	38	2
36°10.9'	106°57.5'	11.5	10	-337	1
36°11.5'	107°28.0'	66.0	854	59	2
36°12.3'	107°19.5'	10.0	60	-82	1
36°12.4'	107°15.2'	10.0	168	-29	1
36°12.6'	107°15.4'	10.0	168	-29	1
36°13.9'	107°07.9'	13.0	47	-42	1
36°14.0'	107°03.0'	56.0	932	43	2
36°15.2'	107°18.5'	11.0	60	-66	1
36°16.0'	107°18.0'	46.0	777	39	2
36°16.5'	106°52.0'	13.5	13	-117	1
36°16.8'	106°03.1'	21.5	16	402	1
36°18.0'	107°09.0'	56.0	959	42	2
36°18.0'	107°34.0'	74.0	1,539	38	2
36°18.2'	107°02.8'	13.5	230	-6	1
36°18.5'	106°03.0'	14.8	17	-12	3 (OJO CAL #2)
36°18.5'	106°03.0'	55.0	26	1,539	3 (OJO CAL #1)
36°19.0'	107°20.0'	81.0	1,293	51	2
36°19.5'	107°17.0'	49.0	893	38	2
36°20.0'	105°57.2'	22.0	198	35	1
36°20.5'	107°30.0'	43.0	707	39	2
36°21.8'	105°46.6'	19.0	117	34	1
36°22.0'	107°35.0'	46.0	818	37	2
36°22.5'	107°25.0'	50.0	764	45	2
36°22.7'	107°00.8'	10.0	52	-96	1

Table 1-1. (Continued).

Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
36°23.5'	107°21.0'	76.0	764	79	2
36°23.5'	107°27.5'	59.0	1,097	40	2
36°24.0'	105°34.5'	14.6	83	-5	3 (TAOS USFS)
36°24.0'	107°15.5'	94.0	1,203	65	2
36°24.6'	105°34.3'	12.5	62	-40	1 (TAOS TOW)
36°24.9'	107°01.3'	11.0	40	-100	1
36°25.1'	106°58.3'	10.0	46	-107	1
36°26.5'	107°10.5'	84.0	1,202	57	2
36°28.4'	105°56.4'	20.0	229	21	1 (COMANCHE)
36°28.5'	107°22.0'	44.0	666	43	2
36°28.7'	105°46.4'	13.0	213	-9	1
36°29.0'	106°51.0'	54.0	904	43	2
36°29.5'	107°24.0'	116.0	2,318	43	2
36°29.9'	107°11.2'	11.0	113	-35	1
36°31.0'	107°12.0'	89.0	1,917	38	2
36°31.8'	105°44.8'	23.5	244	34	1
36°32.4'	105°44.8'	25.5	122	86	1
35°34.0'	106°48.8'	17.0	61	32	1 (RIO SALADO)
36°41.1'	107°32.1'	14.5	111	-4	1
36°41.6'	105°37.1'	8.5	21	-304	1
36°41.7'	105°37.2'	10.0	24	-210	1
36°42.0'	105°25.5'	7.6	65	-114	3 (RED RIV #2)
36°42.5'	105°25.0'	5.8	27	-34	3 (RED RIV #1)
36°45.7'	105°57.4'	29.5	396	36	1
36°51.5'	107°20.5'	123.0	2,575	41	2
36°51.7'	105°36.8'	11.5	45	-78	1
36°51.9'	105°36.8'	10.0	47	-105	1
36°53.5'	106°34.7'	14.5	210	-2	1
34°57.4'	106°26.6'	18.0	215	13	1
36°58.4'	105°31.8'	11.0	76	-52	1 (SANGRE DE)

*Computed negative bottom-hole temperature gradients correspond to wells with bottom-hole temperatures less than the assumed surface temperature of 15°C.

**The information in parentheses is the well identification name used in the original source material.

Sources: 1. USGS GEOTHERM file
2. Swanberg (1980b)
3. Hunter (1983)

Figure 1-4. SiO₂ geotemperatures (°C) of springs and wells in north central New Mexico. The data are compiled from the USGS WATSTORE file and Swanberg (1980a, 1980c).

Figure 1-5. Na-K-Ca geotemperatures (°C) of springs and wells in north central New Mexico. The data are compiled from the USGS WATSTORE file and Swanberg (1980a, 1980c).

Figure 1-6. Sites in north central New Mexico characterized by anomalous actual temperatures ($\geq 22.5^{\circ}\text{C}$) of wells and springs and bottom-hole temperature gradients ($\geq 45^{\circ}\text{C/km}$) of wells.

For bottom-hole depths less than 150 meters, the actual temperatures are chosen to be the corresponding bottom-hole temperatures. Additionally in anomalously warm areas, bottom-hole temperature gradients calculated from very shallow bottom-hole depths can be enhanced because the assumed surface temperature of 15°C is usually substantially lower than the near-surface (i.e., < 50 meters) temperatures in these areas.

In order to compare and determine which areas of the crust are elevated in temperature with respect to the rest of the study area, however, only one surface temperature should be assumed for the whole study area. If an assumed surface temperature of 20°C instead of 15°C was used, then the vast majority of the bottom-hole temperature gradients throughout the study area would be negative and unrealistic, and valuable information would be lost. Even though the bottom-hole temperature gradients may be enhanced to some degree in the Socorro area, the area is, nevertheless, elevated in temperatures with respect to the background temperatures contained within the study area. The amount of contrast between areas of elevated temperatures and normal crustal background temperatures is directly proportional to the magnitude of the bottom-hole temperature gradients. In this way, anomalously warm areas of the crust within the study area may be readily identified and ranked.

Approximately 80 kilometers to the north in the northwest part of Valencia County (see Figure 1-1) is another area of interest. This area is characterized by anomalous actual temperature data but no anomalous bottom-hole temperature gradient data (see Figure 1-6). Figure 1-2 shows that most of the anomalous actual temperatures are between 22.5 and 30°C , with two sites having temperatures just above 30°C . All

of the actual temperature data are from springs and, consequently, no bottom-hole temperature gradients were calculated.

To the immediate north within Bernalillo County, the data plotted in Figure 1-6 suggest three distinct anomalous areas. On the far west side of the county, an anomalous area is suggested by several anomalous bottom-hole temperature gradients but only a couple of anomalous actual temperatures which are in the 22.5 to 30°C range (compare Figures 1-1 and 1-2). Inspection of Table 1-1 shows that the bottom-hole temperatures correspond to relatively shallow depths which could account for the absence of additional anomalous actual temperatures. The two anomalous areas in the central and eastern portions of the county are located on the Albuquerque west and east mesas. The Albuquerque west mesa has undergone substantial geothermal exploration in which shallow (i.e., <30 meters) temperature gradient anomalies have been confirmed by Jiracek et al. (1982). Two temperature gradient anomalies exist on the west mesa, one reaching 140°C/km and another located approximately one mile to the north reaching 107°C/km. These anomalies are small in areal extent, thus indicating shallow sources of limited extent (Jiracek et al., 1982).

Actual temperatures of 34°C at 372 meters and approximately the same temperature, also at 372 meters, were recorded in a USGS water monitoring well and the College #3 Well, respectively. Both wells (the former within and the latter nearby the study area) have linear gradients of approximately 30°C/km. The well record of the Carpenter #1 Atrisco Well, also within the study area, lists zones of large volumes of water at depths of 671, 899, and 1,003 meters; unfortunately, no temperatures were reported. If a local temperature gradient of

30°C/km persists to these depths, then it is possible that the temperature of the fluids at these zones could be 43, 50, and 53°C, respectively (Jiracek et al., 1982).

The anomaly on the Albuquerque east mesa consists mostly of anomalous actual temperatures (see Figure 1-6). Figure 1-2 shows that the actual temperatures are in the range of 22.5 to 30°C and the data of Figure 1-3 suggest that these temperatures are from relatively deep depths. Slightly to the east of the anomalous actual temperatures and low bottom-hole temperature gradients there are some anomalous bottom-hole temperature gradients (see Figure 1-3). Inspection of Table 1-1 shows that these data are from very shallow depths and that the bottom-hole temperatures are low and range from 15 to 22.5°C. Consequently, the high bottom-hole temperature gradients are probably heavily influenced by the choice of the assumed surface temperature of 15°C. These temperature gradients are unlikely to persist with depth.

The biggest anomaly with respect to both areal extent and magnitude within the study area is located in and around the Jemez Mountains, which are situated just to the north of the Albuquerque-Belen Basin (compare Figures 1-1 and 1-6). The dominant tectonic feature of the Jemez Mountains is the Valles Caldera, which is a well-known and documented high-temperature geothermal resource area. Most of the data that comprise this major temperature anomaly seen in Figures 1-2, 1-3, and 1-6 are located within the Valles Caldera system, except for some anomalous data that trend to the southwest from the caldera down off the southwest flank of the Jemez Mountains. Several hot springs which range from 32 to 76°C are located on this southwest flank. Approximately 20 kilometers further to the southwest in and around the San

Ysidro area, both anomalous actual temperatures of wells and springs and bottom-hole temperature gradient data exist (compare Figures 1-1 and 1-6). The maximum actual temperatures in this area are approximately 54°C and the bottom-hole temperature gradients range from 60°C/km to greater than 120°C/km (see Figure 1-3).

Additional areas of anomalous actual temperature and bottom-hole temperature gradient data are shown in the northeast portion of the study area, located near the town of Ojo Caliente and approximately 35 kilometers to the northeast (compare Figures 1-1 and 1-6). The anomalous actual temperature data near the town of Ojo Caliente are mainly from thermal springs which range in temperature from 25 to 56°C; anomalous bottom-hole temperature gradients range from 90°C/km to over 120°C/km. The anomalous data observed to the northeast of Ojo Caliente consist mostly of anomalous actual temperatures and two sites with anomalous bottom-hole temperature gradients. This condition occurs because most of the anomalous actual temperatures are from springs which range from 38 to 41°C. The two anomalous bottom-hole temperature gradients are 34 and 86°C/km for bottom-hole depths of 244 and 122 meters, respectively.

The anomalous actual temperatures located to the east of Los Alamos (compare Figures 1-1 and 1-6) are believed to be from deep depths (see Figure 1-3) and not the result of elevated temperatures. This condition is also believed to be the case for the anomalous actual temperatures located in the northeast corner of McKinley County, although both high and low bottom-hole temperature gradients exist in this area.

Other anomalous temperature areas are located at the sites of Ponce de Leon Springs and Montezuma Hot Springs. The Ponce de Leon Springs

have a surface temperature of 34°C and are located approximately 40 kilometers due east of Ojo Caliente. The Montezuma Hot Springs, located in the northern part of San Miguel County, have a surface temperature of 59°C .

1.3 Anomalous Geotemperature Data

Anomalous geotemperature data are shown in Figure 1-7. Sites having both SiO_2 and Na-K-Ca geotemperatures that indicate reservoir base temperatures equal to or greater than 60 and 70°C , respectively, are considered anomalous within the study area. Figure 1-7 shows whether each anomalous site is characterized by anomalous SiO_2 geotemperature data, Na-K-Ca geotemperature data, or both. Most of the sites of the geotemperature data are located in and around the Albuquerque-Belen Basin, which is situated within the area described as the main temperature anomaly, based on actual temperature and bottom-hole temperature gradient data, within the study area. Consequently, it is not possible to determine if the anomalous geotemperature data define the same anomalous temperature pattern evident in the anomalous actual temperatures and bottom-hole temperature gradient data.

The only area in which there are sites of geotemperature data located outside this generalized anomalous temperature area is in the northeast part of the study area. Examination of Figure 1-4 shows that there are mixed sites of both anomalous and normal SiO_2 geotemperature data in this area. On the other hand, this area is almost free of anomalous Na-K-Ca geotemperature data (see Figure 1-5), with the exception of the Ojo Caliente area and a small area located

Figure 1-7. Sites in north central New Mexico characterized by anomalous SiO₂ (≥60°C) and Na-K-Ca (≥70°C) geotemperatures of springs and wells.

approximately 35 kilometers to the northeast of Ojo Caliente. Both of these areas are also anomalous with respect to actual temperature and bottom-hole temperature gradient data (see Figure 1-6), as well as with respect to SiO_2 geotemperature data (see Figure 1-4).

The main anomaly defined by both SiO_2 and Na-K-Ca geotemperature data is located in the area of the Jemez Mountains (compare Figures 1-1 and 1-7). Much of the anomalous data in this area is directly attributed to the high-temperature hydrothermal system of the Valles Caldera located within the Jemez Mountains. From the caldera, some of the anomalous data trends in a southwest direction down off the southwest flank of the Jemez Mountains and through the San Ysidro area. The SiO_2 and Na-K-Ca geotemperature data, which define this anomalous trend and the two anomalous areas to the northeast near Ojo Caliente, generally exceed 90 and 140°C, respectively (see Figures 1-4 and 1-5).

Most of the other anomalous areas defined by both of the geothermometers generally have at least one of the geotemperature data somewhat lower, but still anomalous as defined for this study, or are based on geotemperature data from a single site. The well-known geothermal resource area near Socorro does not even show up as anomalous with respect to Na-K-Ca geotemperature data and is considered to be just barely anomalous according to the SiO_2 geotemperature data. Other anomalous geotemperature areas occur at the Ponce de Leon Springs and Montezuma Hot Springs.

1.4 Geologic and Geophysical Data

1.4.1 Tectonic Data

Figure 1-8 shows two periods of late-Cenozoic faulting: faults that cut late-Pliocene to Pleistocene (~ 1 to 4 m.y. old) surfaces and

Figure 1-8. Late-Cenozoic faults and major volcanic centers in north central New Mexico. The data are taken from Callender and Seager (1980).

faults that cut late-Quaternary (<1 m.y. old) surfaces. Also shown in Figure 1-8 are Quaternary to late-Pliocene (< 5 m.y. old) rocks and their major volcanic vents including the well-known Valles Caldera. All of the tectonic data in Figure 1-8 are taken from Callender and Seager (1980). The location and age of dated volcanic rocks (Aldrich and Laughlin, 1981) within the study area are shown in Figure 1-9. Also shown in Figure 1-9 are the locations of Quaternary to late-Pliocene volcanic rocks (Callender and Seager, 1980).

Normal faulting dominated both periods of late-Cenozoic faulting, while the faulting within the north central part of the study area during the late-Pliocene to Pleistocene Epoch appears to have been more frequent and dense. Large displacements along the normal faults, particularly during the late-Pliocene to Pleistocene Epoch, are thought to be responsible for the very deep late-Cenozoic basins (i.e., Albuquerque-Belen, Espanola, San Luis). The generalized fault pattern is: a N-S direction from Socorro to Albuquerque, a NNE-SSW direction from Albuquerque to Taos, and both N-S and NW-SE directions from Taos to the Colorado border. Other N-S and NNE-SSW fault trends can be seen, particularly, in the southeast portion of the study area. Two discrete NE-SW fault trends are also evident in Figure 1-8. The northern NE-SW trend is believed to be part of the Jemez Lineament, which intersects with the NNE-SSW fault trend in the vicinity of the Valles Caldera. Together, these two trends are probably responsible for the present position of the caldera and the associated high-temperature hydrothermal system. The other NE-SW trend cuts across Bernalillo and Valencia counties.

Figure 1-9. Ages of dated volcanic rocks in north central New Mexico. The data are taken from Aldrich and Laughlin (1981).

A statewide lineament study (Lepley, 1982), LANDSAT images, and areal photographs clearly show N-S, NNE-SSW, and NE-SW trends intersecting in the Valles Caldera and Jemez Mountain region. The lineament and satellite data also suggest that these and other trends extend outside the study area. Similar trends have been previously reported in the southwest and south central parts of the state (Lohse, 1982 and 1983).

There are three general areas characterized by young volcanic activity (<1.99 m.y. old). By far, the most intense volcanic activity has been in the Valles Caldera area and to a lesser extent in an area centered within Bernalillo, Valencia, and Cibola counties (compare Figures 1-1 and 1-9). The third area is located in the northeast part of Rio Arriba County. Only the volcanic activity in the Valles Caldera area is currently known to be directly associated with a heat source.

1.4.2 Gravity Data

The residual gravity data (Aiken et al., 1978) for the study area are contoured at 5-mgal intervals (see Figure 1-10). Contours representing residual gravity data greater or equal to 20 mgals are constructed with heavy lines to visually enhance the data. The main features displayed by the gravity data are: (1) an elongated N-S oriented residual gravity low associated with the Albuquerque-Belen Basin; (2) a residual gravity minimum associated with the Valles Caldera located just to the north of the Albuquerque-Belen Basin; (3) a regional residual gravity high enclosing the Valles Caldera and the Albuquerque-Belen Basin; and (4) a local residual gravity maximum, situated on the east central portion of the regional residual gravity high, that is associated with the uplifted Paleozoic and Precambrian

Figure 1-10. Residual Bouguer gravity map of north central New Mexico [from Aiken et al. (1978)].

strata of the Manzano and Sandia mountains.

When the regional gravity high is combined with the two enclosed gravity lows, there is a strong NNE-SSW orientation to the resulting elongated geometrical shape created by the associated gravity contours. This NNE-SSW trending gravity structure is transversed by several strong approximately N-S trends that pass through the center of the study area. Two other trends, which may represent grains of weakness in the crust, are suggested by the gravity data. The stronger grain is defined by moderately strong NE-SW trends that cross the study area through Torrance and Socorro counties (compare Figures 1-1 and 1-10) in the south, from the northeast corner of the study area down through the Valles Caldera and coincident with the Jemez Lineament in the north, and across the central part of the study area from 36° latitude on the east to just below 35° latitude on the west. The weaker grain is oriented in a NW-SE direction and can be seen in the northeast and southwest corners of the study area (see Figure 1-10).

Much has been learned about the subsurface structure of the Albuquerque-Belen Basin based upon extensive two-dimensional gravity modeling by Birch (1980) using four density units. According to Birch (1980), the upper layer (density = 2.20 gm/cm^3) corresponds to Neogene post-rifting deposits that comprise the principal aquifer in the basin. The thickness of this layer averages 1.5 kilometers and exceeds 2.5 kilometers in a N-S strip along the eastern side of the basin. The second layer (density = 2.40 gm/cm^3) includes Jurassic, Cretaceous, and Paleogene strata and averages 1.5 kilometers in thickness. The maximum thickness is in an E-W strip along $34^{\circ}50'$ latitude. The third layer (density = 2.57 gm/cm^3) is composed of Paleozoic and

Triassic sedimentary rocks and averages about 1.0 kilometer in thickness, with a maximum thickness of about 2.0 kilometers in an E-W band along 35° latitude. The final unit (density = 2.67 gm/cm³) is the Precambrian crystalline basement, which ranges in elevation (based on mean sea level) from -4.0 kilometers under parts of the basin to over +3.0 kilometers in the bordering mountains. Average elevation of the basement in the basin is rather constant at about -3.0 kilometers. The eastern sides of the basement typically descend more steeply into the basin than the western sides.

1.5 Summary

An analysis of temperature and geotemperature data from numerous sites throughout north central New Mexico results in several important observations. Actual temperature and bottom-hole temperature gradient data both suggest that two separate thermal regimes characterize the background temperatures in the upper crust within the study area. This result is suggested by the fact that there is almost a total absence of actual temperatures less than 15°C within the crust in the southwest portion of the study area.

Superimposed upon these regional background temperatures are a very large thermal anomaly, located throughout the center of the study area containing both high- and low-temperature resources, and several isolated low-temperature resource areas located in the northeast portion of the study area. The large thermal anomaly appears to be associated with the Albuquerque-Belen Basin in that most of the anomalous actual temperature and bottom-hole temperature gradient data are located within and around the basin. More precisely, the anomalous temperature data

appear to be associated with the western edge of the basin. The Valles Caldera, a well-known high-temperature resource area, appears properly as a major temperature anomaly and is located in the Jemez Mountains on the extreme northern end of the Albuquerque-Belen Basin at the intersection of the NE-SW trending Jemez Lineament and NNE-SSW trending faults. Anomalous SiO_2 and Na-K-Ca geotemperature data also indicate a major thermal anomaly in and around the Jemez Mountains and the Valles Caldera area. Both types of anomalous geotemperature data are also present in each of the low-temperature resource areas identified by the anomalous temperature data in the northeast portion of the study area. A very limited number of sites with geotemperature data exist over most of the rest of the study area, which prevents any identification of a regional pattern indicating the presence of two thermal regimes similar to those displayed by the temperature data.

Regional residual gravity, lineament data, satellite imagery, and late-Cenozoic fault patterns were analyzed for possible correlations with trends suggested by the anomalous temperature and geotemperature data. Both the gravity and fault data suggest that four possible trends of structural control may be present in the upper crust within the study area. A general N-S trend and a NNE-SSW trend appear as the dominant grains because these trends appear to have controlled the general direction of late-Cenozoic faulting and the major trends apparent in the residual gravity data. Both data sets also show moderately strong NE-SW trends and somewhat weaker NW-SE trends. Lineament data and LANDSAT and SKYLAB images and mosaics also show these trends and suggest that they extend out beyond the boundaries of the study area.

Figure 1-11 shows the sites characterized by anomalous temperature and/or geotemperature data, along with the approximate orientations (represented by the bold lines around the shaded areas) of the dominant fracture zones suspected of controlling the subsurface structure. These fracture zones are inferred mainly from late-Cenozoic fault patterns, major trends defined by gravity gradients, and anomalous temperature and geotemperature data from this study.

A close spatial relationship appears to exist between the general trends and areas defined by anomalous temperature and geotemperature data (see Figure 1-11), the late-Cenozoic faulting patterns (see Figure 1-8), and the major gravity gradients associated with west-side basin boundary faults and the NE-SW grains correlated with the Jemez Lineament (see Figure 1-10). This condition suggests that most of the hydrothermal activity is probably fault controlled. It is also believed that pre-existing trends or grains of structural weakness in the basement (Paleozoic or Precambrian) are responsible for the current tectonic setting and the preferential directions of late-Cenozoic faulting. The general agreement between the age and location of late-Cenozoic faulting and volcanism (see Figures 1-8 and 1-9, respectively), coupled with the presence of an anomalous thermal regime (see Figure 1-11), suggests that a direct relationship might exist among these three features. It is also possible that the thermal anomalies and tectonic activity are related to the source of a residual gravity high (ridge) that coincides with both the thermal and tectonic features throughout most of the study area. The ridge, defined by the residual gravity high located in the western portion of the study area, may be

Figure 1-11. Probable low-temperature geothermal resource areas in north central New Mexico. Low-temperature geothermal resources have been identified in some of these areas and a high-temperature reservoir has been confirmed in the Valles Caldera area.

related to a late-Cenozoic upwarping of the mantle generally believed to be occurring throughout this area within the Rio Grande Rift system.

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2.0 Measured Geothermal Gradients in North Central New Mexico*

2.1 Introduction

This study was initiated to collect and integrate data on geothermal gradients in north central New Mexico and to identify areas with characteristics favorable for the development of low-temperature geothermal resources. Temperature gradients were measured in 22 water wells and potentially favorable areas for geothermal resource development were identified at Santa Ana Pueblo, Ojo Caliente, La Cueva, and Taos.

2.2 Research Methodology

2.2.1 Data Sources and Previous Work

New data for this study were obtained by measuring thermal gradients in existing water wells. Other major data sources include gradients compiled by Kron and Heiken (1980) and by Swanberg (1980). Both of these sources represent major compilations and reviews of existing data, the sources of which are listed in the Bibliography.

2.2.2 Data Collection

Existing water wells were logged with a Fluid Dynamics thermistor probe. Data were recorded at discrete intervals because the equipment was not designed for continuous recording. Selection of logging intervals depended on the well depth, whether the well was water-filled or dry, and the available time.

* The principal author of Chapter 2 is James C. Hunter, Los Alamos National Laboratory.

Shallow domestic water wells were usually logged at 1- or 2-meter intervals, whereas deeper (i.e., generally greater than 100 meters) wells were logged at 5- to 10-meter intervals. The logging device has a useful battery life of about 3 hours, which required logging to be completed within that time. The battery-life problem was also important when logging dry wells because the thermistor probe requires at least 5 minutes to equilibrate in air. This condition puts a limit of about 30 data collection intervals, not counting set-up and testing time, on dry wells. In addition, many owners and/or users of domestic and irrigation wells were concerned about the length of time that a well would be out of service. Very few people were willing or able to suspend well pumping for the minimum of 48 hours necessary for the well to reach thermal equilibrium.

2.2.3 Well Selection

A systematic sample of water wells in north central New Mexico was difficult to obtain because of a number of problems. The major problems encountered were: (1) locating wells suitable for logging, (2) identifying and contacting well owners, (3) obtaining permission to log the wells, (4) gaining physical access to the well, (5) shutting down pumping operations for several days, (6) opening or dismantling wellhead devices to allow insertion of the thermistor probe, and (7) inclement weather conditions.

Primary sources of well locations included the U.S. Geological Survey, the New Mexico State Engineer's Office, county and municipal governments, and Indian tribal offices. The governments of all counties, Indian organizations, and major municipalities in north central New Mexico were contacted. Four of these government organizations

responded, of which two were interested in participating, one declined to cooperate, and the other claimed to be unable to help. Data provided by the U.S. Geological Survey (USGS) included a computer listing of all of the USGS water-quality and flow-measuring localities. This listing does not distinguish wells from springs or streams. The Office of the New Mexico State Engineer had information on well locations, but ownership information was frequently out of date and lacked current addresses of owners. Private landowners were frequently reluctant to participate in any program which did not appear to benefit them directly or immediately.

Physical access to wells was a major problem. The study began in the fall, and by early winter most rural roads were impassable. This problem continued through the spring. By the time that the weather had improved and the roads had become dry and passable, the irrigation season had begun. Few, if any, well owners were willing to suspend pumping for any length of time during this critical period.

Water wells are equipped with a wide variety of wellhead devices for pumping and distributing water. Many of these devices rendered the well bore inaccessible to the thermistor probe. In view of the very large financial liabilities involved if a well was damaged, no attempts were made to dismantle wellhead devices.

In light of these problems, an effort was made to publicize the study in the hope that well owners would volunteer access to their wells. Articles describing the project were run in all northern New Mexico newspapers. Approximately 20 persons inquired, but problems of well shutdown, scheduling, and wellhead configurations left only 5 wells available for data collection. Although domestic, municipal, and

industrial water wells represent substantial opportunities for data collection, the problems encountered in this study will continue to frustrate efforts to utilize this data source.

2.2.4 Temperature Gradient Calculations

Thermal gradients were calculated by fitting a least-squares line to the temperature-depth data. In all cases, the temperature-depth plot was visually inspected, and data above the near-surface seasonal temperature curve inflection was eliminated from the calculation. In wells with a water column, no data was used from above the water level. Gradient intervals for dry wells represent intervals where visually smooth data exist.

2.2.5 Data Presentation Format

Temperature gradient measurements from the 22 wells logged are summarized in Table 2-1. Detailed temperature-depth data are tabulated and plotted in Appendices A and B, respectively. Although data from all wells logged are given in Table 2-1 and Appendix A, only those with positive temperature gradients over the specified interval equal to or greater than $10^{\circ}\text{C}/\text{km}$ are included in Figures 2-1 through 2-3.

Figure 2-1 shows selected temperature gradient data in New Mexico. Figure 2-2 contains average temperature gradients per 10-minute square. Squares for which no temperature data were used are left blank. The areal coverage is about 11.5 percent. Temperature contours of $10^{\circ}\text{C}/\text{km}$ based on the data of Figures 2-1 and 2-2 are shown in Figure 2-3.

Figure 2-4 is a generalized geologic map of New Mexico. The Great Plains region and the Colorado Plateau are characterized by temperature gradients of about $30^{\circ}\text{C}/\text{km}$. The Rio Grande Rift, the Datil-Mogollon

Table 2-1. Measured geothermal gradients in north central New Mexico.

Well Name	Latitude DG/MN/SC	Longitude DG/MN/SC	Depth (m)	Depth Interval (m)	Interval Gradient (°C/km)	Bottom-Hole Temperature (°C)	Remarks*
SAP/GP	35/18/00	106/33/00	31	16-31	-9.1	16.5	NSGW ?
SAP/LV	35/20/00	106/32/00	34	8-34	61.2	17.6	
SAP/JD1	35/24/00	106/34/00	23	20-23	69.3	13.1	
SAP/JD2	35/24/00	106/34/00	120	84-120	5.9	15.7	TOPO ?
CAJA #4	35/45/59	106/09/13	390	20-390	41.1	26.6	Dry
Pojaque	35/53/00	106/02/00	56	24-56	8.0	14.6	NSGW
La Cueva	35/52/30	106/37/30	47	38-47	358	27.5	ELE ?
Ponderosa	35/49/00	106/35/00	31	16-28	76.4	12.9	
LV/IM3	35/53/00	106/57/30	122	56-122	25.8	14.5	
LV/IM4	35/52/50	106/59/32	282	65-282	29.9	19.0	
LV/IM5	35/53/36	106/59/30	210	27-210	28.7	17.4	
LV/IM6	35/54/30	106/59/35	348	44-348	35.1	22.0	
Jaconita	35/57/00	106/10/00	39	9-39	-22	14.3	NSGW ?
Garcia #1	35/57/21	106/14/25	290	30-290	53.5	23.3	Dry
Cundayo	35/58/00	105/54/00	45	9-45	34.3	11.9	
Khalsa	36/02/30	106/14/00	290	10-206	51.5	23.5	Dry
Penasco	36/10/00	106/14/00	35	15-35	2.0	10.4	NSGW ?
Ojo Cal #2	36/18/27	106/02/58	17	6-16	77.0	14.8	Abandoned water well, about 600 m east of hot springs
Ojo Cal #1	36/18/29	106/02/57	26	9-25	67.0	55.0	Unused hot-water well at hot springs resort
Taos USFS	36/24/00	105/34/30	83	2-83	53.1	14.6	Dry
Red Riv #2	36/42/00	105/25/30	65	60-65	27.8	7.6	
Red Riv #1	36/42/30	105/25/00	27	5-27	74.0	5.8	

* NSGW - Near-surface groundwater effects: Negative or near-zero gradients may be due to penetrations of colder aquifers.

ELE - Extreme local effects: Extremely high near-surface gradient, possibly due to penetration of ascending limits of thermal convection cell, penetration of hot aquifer.

TOPO - Topographic effects: This well (SAP/JD2) is located near the edge of a steep mesa with ~100 m of relief. Lower part of this well may be closer to free surface than depth would indicate.

NEW MEXICO GEOTHERMAL GRADIENTS

DATA SOURCES

- JC HUNTER, this study
- STIX and KRON, 1982

Figure 2-1. Selected temperature gradients in New Mexico. The data are given in units of $^{\circ}\text{C}/\text{km}$.

AVERAGE NEW MEXICO GEOTHERMAL GRADIENTS BY 10 - MINUTE SQUARES

Figure 2-2. Average geothermal gradients in New Mexico.

CONTOURED NEW MEXICO GEOTHERMAL GRADIENTS

CONTOUR INTERVAL 10 °C/km

Figure 2-3. Geothermal gradient contours in New Mexico.

GENERALIZED GEOLOGIC MAP OF NEW MEXICO

Figure 2-4. Generalized geologic map of New Mexico.

volcanic field, and the Basin and Range Province are correlated with positive anomalies ranging from 40 to 90°C/km (compare Figures 2-3 and 2-4).

2.3 Discussion

Because of the problems discussed with respect to selecting wells, the data collected by this study cannot be considered to represent an unbiased sample of geothermal gradients in north central New Mexico; however, some potentially favorable areas for further study may be identified. A favorable area is defined as having: (1) gradients greater than 40°C/km, (2) an adequate supply of groundwater, (3) a nearby existing or potential user, and (4) a local interest in the application of geothermal resources.

One area where all four criteria appear to be met is Santa Ana Pueblo, near Bernalillo, New Mexico. Relatively shallow (i.e., 20- to 100-meter) water wells reveal groundwater temperatures of 16°C or greater, with gradients in the range of 40 to 60°C/km. Good quality groundwater is available and the Santa Ana Pueblo government is very interested in geothermal energy development.

Santa Ana Pueblo is located in the northern Albuquerque Basin of the Rio Grande Rift. Surface exposures are limited to generally east-dipping sediments of the Santa Fe group with localized basaltic flows, dikes, plugs, and maar deposits. Post-Santa Fe deposits are of alluvial, colluvial, and fluvial material of Plio-Pleistocene age (see Figure 2-5). The Neogene stratigraphy of this area has been mapped and described by Hoge (1971).

GEOLOGIC MAP OF THE SANTA ANA AREA

BASE : USGS SANTA ANA, BERNALILLO NE AND PLACITAS 7½ QUADRANGLES

- FLOOD PLAIN AND CHANNEL DEPOSITS OF ACTIVE STREAMS, MUD, SAND AND GRAVEL
- EOLIAN SAND DEPOSITS, SHEETS AND DUNES
- OLDER ALLUVIAL AND FLUVIAL DEPOSITS, MUD, SAND AND GRAVEL
- TALUS DEPOSITS OF QTb, DERIVED FROM SANTA ANA BASALT, MAPPED WHERE CONTIGUOUS
- OLDER TERRACE AND FAN DEPOSITS
- SANTA ANA BASALT; FLOWS, DIKES, PLUGS AND MAAR DEPOSITS
- SANTA FE GROUP, UNDIVIDED
- COCHITI FORMATION OF SANTA FE GROUP, LITHIC ARKOSIC SANDS WITH PREDOMINANTLY VOLCANIC LITHICS
- ALTERED, FE-STAINED Tc, LOCALIZED AROUND CANJILLON HILL

Figure 2-5. Geologic map of the Santa Ana Pueblo area.

Intra-rift structure is dominated by the northwest-trending San Felipe fault zone (Hoge, 1971), a set of west-dipping (58 to 80°) normal faults with a displacement of 3 to 39 meters. Where exposed near Jemez Canyon Dam, these faults are zones of calcified breccia (see Figure 2-5). If this cementation persists at depth, these faults may act as permeability barriers, channeling groundwater from recharge areas in the southern Jemez Mountains down the southeasterly hydraulic gradient mapped by Titus (1961).

The area immediate to Santa Ana Pueblo is dominated by the Santa Ana Mesa, which is formed by a resistant cap of 2.16 to 2.6 million-year-old basalt (Aldrich and Laughlin, 1981) overlying arkosic sediments of the Cochiti Formation (Smith et al., 1970). The faults of the San Felipe zone cut this basalt, placing an age constraint on the faulting.

Figure 2-6 is an overlay for Figure 2-5 and shows the locations of the wells logged as part of this study, wells with bottom-hole temperature data only, proposed resistivity sounding sites, and proposed test well sites. The proposed test area is in the projected extension of the San Felipe fault zone, between Santa Ana Mesa and Canjilon Hill. The test area has been chosen on the basis of tectonics, the temperature of a nearby water well (WEP-1), access, and current land use. At present, the area is used as sparse grazing land. If significant geothermal potential exists, the Santa Ana Pueblo is interested in developing year-round greenhouse farming on this site.

Four wells were logged on Santa Ana Pueblo lands. The most promising data come from the lower village well (SAP-LV), which has a

LOCATION OF LOGGED WELLS, OTHER TEMPERATURE DATA WELLS,
PROPOSED TEST WELLS AND PROPOSED RESISTIVITY SOUNDING SITES

DEPTH (m) | BHT °C
GRADIENT (°C/km)

- WELL LOGGED IN THIS STUDY
- ▲ WELL DATA PROVIDED BY WESTERN ENERGY PLANNERS
- PROPOSED TEST WELL SITES
- PROPOSED RESISTIVITY SOUNDING SITE

Figure 2-6. Location of geothermal exploration activities in the Santa Ana Pueblo area.

gradient of about $60^{\circ}\text{C}/\text{km}$ and a bottom-hole temperature of $17.6^{\circ}\text{C}/\text{km}$ at a depth of 34 meters.

Ojo Caliente is a well-known hot spring site (Summers, 1976) which has been developed into a small resort offering lodging and mineral baths. Gradients in this area range from 67 to $77^{\circ}\text{C}/\text{km}$, and water temperatures as high as 55°C have been measured (see Table 2-2 and Appendix A). The hot springs appear to be controlled by a fault zone which juxtaposes horst blocks of Precambrian basement against Tertiary sediments (Stix et al., 1982). Potential exists for either direct or heat-pump assisted geothermal applications at Ojo Caliente.

The La Cueva area is located in the Jemez Mountains, near the southeastern edge of the Valles Caldera. The La Cueva Well (see Table 2-1) has the highest gradient ($358^{\circ}\text{C}/\text{km}$) measured in this study, with a bottom-hole temperature of 27.5°C . This area has substantial potential for direct or heat-pump assisted space heating.

The Taos-Red River area has not been explored in great detail, but available information suggests that good geothermal potential may exist. Several hot springs are known in this area (Summers, 1976), and local gradients as high as $74^{\circ}\text{C}/\text{km}$ have been measured.

Several factors contribute to the favorable aspects of this area. Known hot springs with temperatures of 34 to 41°C discharge along the Rio Grande in Taos gorge and at Ponce de Leon springs along the eastern rift boundary fault zone (Swanberg, 1980; Summers, 1976). The Taos Plateau is capped by 1.84 to 3.35 million-year-old basaltic rocks (Lipman, 1979), and the local heat flow is 2.5 HFU (Swanberg, 1980).

Further study of existing wells on or near the Taos Plateau would be very useful. This area is experiencing moderate population growth,

and any additional energy resources would be extremely useful. Although ski resorts might be potential users, these industries are generally located in the mountains to the east of the rift, where aquifers are shallow and groundwater temperatures are low. The best areas for potential geothermal energy applications appear to be the town of Taos and neighboring villages and ranches.

2.4 Conclusions

Santa Ana Pueblo is the only area identified by this study which has indications of geothermal resources, adjacent potential users, and local interest in development of geothermal resources. The La Cueva, Ojo Caliente, and Taos areas have geological indications of potential geothermal resources, but lack adjacent possible users at this time.

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APPENDIX A

Temperature Data for North Central New Mexico

Note: Temperature gradients are computed for each depth interval. Extrapolated surface temperatures have been used to calculate the temperature gradient from the surface to the first measured value.

Well Name: SAP/GP

<u>Depth</u> (m)	<u>Temperature</u> (°C)	<u>Temperature</u> <u>Gradient</u> (°C/km)
7.5	16.84	645
10	17.21	148
12	17.06	-75
14	16.77	-145
16	16.57	-100
18	16.55	-10
20	16.54	-5
22	16.46	-40
24	16.45	-5
26	16.43	-10
28	16.41	-10
30	16.45	20
31	16.46	10

Well Name: SAP/LV

<u>Depth (m)</u>	<u>Temperature (°C)</u>	<u>Temperature Gradient (°C/km)</u>
8	15.8	475
10	16.1	150
12	16.3	100
14	16.3	0
16	16.4	50
18	16.5	50
20	16.5	0
22	16.7	100
24	16.8	50
26	17.0	100
28	17.1	50
30	17.2	50
32	17.4	100
33.7	17.6	118

Well Name: SAP/JD1

<u>Depth (m)</u>	<u>Temperature (°C)</u>	<u>Temperature Gradient (°C/km)</u>
20	12.82	41
22	12.87	25
22.7	13.05	257

Well Name: SAP/JD2

<u>Depth (m)</u>	<u>Temperature (°C)</u>	<u>Temperature Gradient (°C/km)</u>
84	15.53	42
86	15.51	-10
88	15.53	10
90	15.53	0
92	15.55	10
94	15.55	0
96	15.56	5
98	15.56	0
100	15.58	10
102	15.58	0
104	15.60	10
106	15.60	0
108	15.61	5
110	15.65	20
112	15.67	10
114	15.68	5
116	15.70	10
118	15.70	0
120	15.74	20

Well Name: CAJA #4

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°C/km)</u>
20	12.34	17
40	13.20	43
60	13.84	32
80	14.74	45
100	15.45	36
120	16.05	30
140	16.68	32
160	17.25	29
180	18.04	40
200	19.27	62
220	20.41	58
240	21.39	49
260	22.36	49
280	23.27	46
300	24.07	40
320	24.79	36
340	25.54	38
360	25.97	22
380	26.47	25
390	26.63	16

Well Name: Pojoaque

<u>Depth (m)</u>	<u>Temperature (°C)</u>	<u>Temperature Gradient (°C/km)</u>
2	10.33	-835
4	11.53	600
6	13.00	735
8	13.67	335
10	13.75	40
12	13.75	0
14	13.64	-55
16	13.57	-35
18	13.56	-5
20	13.65	45
22	13.82	85
24	13.97	75
26	14.06	45
28	14.06	0
30	14.12	30
32	14.12	0
34	14.16	20
36	14.16	0
38	14.19	15
40	14.24	25
42	14.25	5
44	14.25	0
48	14.30	0.4
50	14.40	50
52	14.48	40
54	14.56	40
55.7	14.56	0

Well Name: La Cueva

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°C/km)</u>
38	24.21	321
39	24.41	200
40	24.71	300
41	25.33	620
42	25.52	190
43	25.77	250
44	26.30	530
45	26.52	220
46	26.84	320
47	27.46	620

Well Name: Ponderosa

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°C/km)</u>
6	13.07	178
8	13.01	-30
10	13.26	125
12	13.14	-60
14	13.11	-15
16	13.11	0
18	13.20	45
20	13.26	30
22	13.40	70
24	13.58	90
26	13.89	155
28	13.97	40
30	12.98	-495
30.8	12.86	-150

Well Name: LV/IM3

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°C/km)</u>
50	13.08	-
52	13.02	-30
54	12.79	-12
56	12.77	-10
58	12.82	25
60	12.86	20
62	12.90	20
64	12.96	30
66	13.02	30
68	13.07	25
70	13.11	20
72	13.17	30
74	13.23	30
76	13.29	30
78	13.34	25
80	13.40	30
82	13.44	20
84	13.50	30
86	13.56	30
88	13.61	25
90	13.66	25
92	13.72	30
94	13.77	25
96	13.81	20
98	13.86	25
100	13.90	20
102	13.97	35
104	14.01	20
106	14.06	25
108	14.11	25
110	14.15	20
112	14.20	25
114	14.25	25
116	14.31	30
118	14.36	25
120	14.41	25
122	14.46	25
122.5	14.47	20

Well Name: LV/IM4

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)
62	12.60	10
65	12.58	-7
70	12.65	14
75	12.89	48
80	13.01	24
85	13.11	20
90	13.28	34
95	13.44	32
100	13.66	44
105	14.03	74
110	14.14	22
115	14.31	34
120	14.30	-2
125	14.52	44
130	14.79	54
135	14.87	16
140	14.97	20
145	15.12	30
150	15.30	36
155	15.57	54
160	15.74	34
165	15.98	48
170	16.03	10
175	16.20	34
180	16.27	14
185	16.25	-4
190	16.43	36
195	16.60	34
200	16.74	28
205	16.92	36
210	17.09	34
215	17.23	28
220	17.38	30
225	17.52	28
230	17.67	30
235	17.84	34
240	17.99	30
245	18.10	22
250	18.24	28
255	18.37	26
260	18.53	32
265	18.64	22
270	18.72	16
275	18.82	20
280	18.90	16
281.9	18.95	28

Well Name: LV/IM5

<u>Depth (m)</u>	<u>Temperature (°C)</u>	<u>Temperature Gradient (°C/km)</u>
27	12.21	8
30	12.26	17
35	12.38	24
40	12.49	22
45	12.60	22
50	12.65	10
55	12.79	28
60	12.90	22
65	13.05	30
70	13.26	42
75	13.29	6
80	13.43	28
85	13.83	80
90	13.81	-4
95	14.15	68
100	14.12	-6
105	14.42	60
110	14.25	-34
115	14.36	22
120	14.50	28
125	14.63	26
130	14.84	42
135	14.97	26
140	15.06	18
145	15.28	44
150	15.40	24
155	15.59	38
160	15.74	30
165	15.96	44
170	16.13	34
175	16.30	34
180	16.46	32
185	16.64	36
190	16.80	32
195	16.89	18
200	16.97	16
205	17.21	48
210	17.43	44

Well Name: LV/IM6

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)
44	11.49	-
46	11.55	30
48	11.60	20
50	11.66	30
52	11.73	35
54	11.81	40
56	11.88	35
58	11.97	45
60	12.04	35
62	12.11	35
64	12.18	35
66	12.25	35
68	12.32	35
70	12.34	10
72	12.47	35
74	12.54	35
76	12.61	35
78	12.65	20
80	12.76	55
82	12.82	30
84	12.89	35
86	12.96	35
88	13.02	30
90	13.08	30
92	13.14	30
94	13.20	30
96	13.26	30
98	13.32	30
100	13.38	30
102	13.44	30
104	13.52	40
106	13.58	30
108	13.66	40
110	13.77	55
112	13.84	35
114	13.94	50
116	13.98	20
118	14.03	25
120	14.09	30
122	14.15	30
124	14.23	40
126	14.33	50
128	14.42	45
130	14.47	25
132	14.57	50
134	14.62	25
136	14.65	15
138	14.68	15

LV/IM6 (continued)

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)
140	14.81	65
142	14.87	30
144	14.92	25
146	15.02	50
148	15.14	60
150	15.17	15
152	15.22	25
154	15.35	65
156	15.47	60
158	15.47	0
160	15.52	25
162	15.54	10
164	15.57	15
166	15.59	10
168	15.59	0
170	15.62	15
172	15.87	125
174	15.96	45
176	16.03	35
178	16.10	35
180	16.22	60
182	16.29	35
184	16.34	25
186	16.41	35
188	16.53	60
190	16.60	35
192	16.64	20
194	16.71	35
196	16.76	25
198	16.78	40
200	16.87	45
202	16.94	35
204	17.01	35
206	17.16	75
208	17.19	15
210	17.21	15
212	17.30	45
214	17.43	65
216	17.49	30
218	17.54	25
220	17.62	40
222	17.71	45
224	17.78	35
226	17.86	40
228	17.95	45
230	18.01	30
232	18.07	30

LV/IM6 (continued)

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)
234	18.14	35
236	18.22	35
238	18.29	35
240	18.35	30
242	18.41	30
244	18.51	50
246	18.58	35
248	18.66	40
250	18.74	40
252	18.80	30
254	18.88	40
256	18.96	40
258	19.01	25
260	19.09	40
262	19.15	30
264	19.23	40
266	19.29	30
268	19.35	30
270	19.43	40
272	19.51	40
274	19.58	35
276	19.66	40
278	19.74	40
280	19.80	30
282	19.88	40
284	19.94	30
286	20.01	35
288	20.07	30
290	20.13	30
292	20.21	40
294	20.28	35
296	20.34	30
298	20.40	30
300	20.47	35
302	20.51	20
304	20.59	40
306	20.68	45
308	20.74	30
310	20.83	45
312	20.89	30
314	20.98	45
316	21.02	20
318	21.09	35
320	21.18	45
322	21.22	30
324	21.28	30
326	21.35	35
328	21.42	35

LV/IM6 (continued)

<u>Depth (m)</u>	<u>Temperature (°C)</u>	<u>Temperature Gradient (°C/km)</u>
330	21.48	30
332	21.53	25
334	21.59	30
336	21.64	25
338	21.73	45
340	21.77	20
342	21.84	35
344	21.91	35
346	21.95	20
348	22.02	35
348.3	22.04	-

Well Name: Jaconita

<u>Depth (m)</u>	<u>Temperature (°C)</u>	<u>Temperature Gradient (°C/km)</u>
9	14.32	258
10	14.32	0
12	14.32	0
14	14.32	0
16	14.32	0
18	14.27	-25
20	14.19	-40
22	14.08	-55
24	14.05	-15
26	14.04	-5
28	14.05	5
30	14.07	10
32	14.08	5
34	14.10	10
36	14.14	20
38	14.19	25
39	14.27	80

Well Name: Garcia #1

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°C/km)</u>
30	9.8	-
60	11.4	53
90	12.3	30
120	13.4	37
150	14.5	37
180	16.0	50
210	18.2	73
240	20.1	63
266	21.9	69
270	22.1	50
275	22.2	20
280	23.0	160
285	23.1	20
286	23.3	200

Well Name: Cundayo

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°C/km)</u>
9	10.68	-147
10	10.66	-20
12	10.76	50
14	10.84	40
16	10.92	40
18	10.97	25
20	11.01	20
22	11.06	25
24	11.08	10
26	11.12	20
28	11.27	75
30	11.34	35
32	11.40	30
34	11.48	40
36	11.56	40
38	11.64	40
40	11.70	30
42	11.80	50
44	11.86	30
45	11.92	60

Well Name: Khalsa

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)
10	13.40	140
15	13.53	26
20	13.69	32
25	13.79	20
30	13.98	38
35	14.81	166
40	14.38	-86
45	14.55	34
50	14.78	46
55	15.07	58
60	15.22	30
65	15.45	46
70	15.69	48
75	16.03	68
80	16.27	48
85	16.41	28
90	16.58	34
95	16.92	68
100	17.21	58
105	17.62	82
110	17.97	70
115	18.29	64
120	18.45	32
125	18.82	74
130	19.09	54
135	19.35	52
140	19.58	46
145	19.84	52
150	20.19	70
155	20.38	38
160	20.42	8
164	20.42	0
170	21.02	100
175	21.35	66
180	21.48	26
185	21.77	58
190	22.11	68
195	22.48	74
200	22.85	74
205	23.11	52
206.4	23.52	315

Well Name: Penasco

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°C/km)</u>
1	8.72	-3,280
2	8.70	-20
3	8.82	120
4	9.04	220
5	9.22	180
6	9.42	200
7	9.54	120
8	9.60	60
9	9.71	110
10	9.78	70
11	9.77	-10
12	9.82	50
13	9.90	80
14	10.15	250
15	10.22	70
16	10.27	50
17	10.27	0
18	10.28	10
19	10.27	-10
20	10.27	0
21	10.26	-10
22	10.30	40
23	10.34	40
24	10.32	-20
25	10.34	20
26	10.32	-20
27	10.32	0
28	10.31	-10
29	10.34	30
30	10.40	60
31	10.34	-60
32	10.34	0
33	10.31	-30
34	10.26	-50
34.5	10.36	200

Well Name: Ojo Cal #2

<u>Depth (m)</u>	<u>Temperature (°C)</u>	<u>Temperature Gradient (°C/km)</u>
2	12.09	-1,780
4	13.27	590
6	13.48	105
8	13.64	80
10	13.74	50
12	13.85	55
14	14.00	75
16	14.13	65
16.7	14.81	971

Well Name: Ojo Cal #1

<u>Depth (m)</u>	<u>Temperature (°C)</u>	<u>Temperature Gradient (°C/km)</u>
1.3	52.76	31,354
3.3	53.90	570
5.3	54.42	260
7.3	54.67	125
9.3	54.76	45
11.3	54.78	10
13.3	54.82	20
15.3	54.83	5
17.3	54.83	0
19.3	54.89	30
21.3	54.91	10
23.3	54.94	15
25.3	54.95	5

Well Name: Taos USFS

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°C/km)</u>
1.5	0	-8,000
5	9.8	2,800
10	11.1	260
15	11.3	40
20	11.4	20
25	11.6	40
30	11.7	20
35	11.9	40
40	12.2	60
45	12.4	40
50	12.7	60
55	12.8	20
60	13.1	60
65	13.4	60
70	13.7	60
75	14.5	160
80	14.6	20
82.6	14.6	0

Well Name: Red Riv #2

<u>Depth (m)</u>	<u>Temperature (°C)</u>	<u>Temperature Gradient (°C/km)</u>
38	7.33	-123
40	7.34	5
42	7.30	-20
44	7.28	-10
46	7.27	-5
48	7.24	-15
50	7.23	-5
52	7.22	-5
54	7.21	-5
56	7.21	0
58	7.41	100
60	7.44	15
62	7.50	30
64	7.57	35
65	7.57	0

Well Name: Red Riv #1

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°C/km)</u>
5	3.98	-1,604
7	4.28	150
10	4.75	156.67
12	5.00	125
14	5.05	25
16	5.13	40
18	5.19	30
20	5.27	40
22	5.28	5
24	5.67	195
26	5.78	55
27	5.84	60

APPENDIX B

Temperature-Depth Data for North Central New Mexico

Note: Straight lines on the temperature-depth plots represent least-squares fits to the data for the specified interval. The lines on the gradient plots correspond to the interval-to-interval change in the gradient as a function of depth.

WELL SAP/GP

WELL SAP/LV

SAP/JD1

WELL SAP/JD2

WELL CAJA #4

WELL POJOAQUE

WELL LA CUEVA

WELL PONDEROSA

LV/IM3

LV/IM4

LV/IM5

LV/IM6

WELL JACONITA

WELL GARCIA #1

CUNDAYO

WELL KHALSA

WELL PENASCO

WELL OJO CAL #1

OJO CAL #2

WELL TAOS USFS

WELL RED RIV #1

WELL RED RIV #2

3.0 Temperature Gradient Studies Near Two Groundwater Constrictions in Northern New Mexico*

3.1 Introduction

The Embudo and La Bajada constrictions are two groundwater constrictions located in north central New Mexico. Groundwater constriction theory suggests that both should be associated with geothermal resources yet no geothermal discoveries have been made, quite likely due to the lack of data and/or the lack of a suitable geothermal investigation. The purpose of the present investigation was to locate and thermally log all available wells near these two constrictions and to supplement these data with temperature-depth data (taken from oil, gas, and water wells), geochemical data, and any other appropriate data in order to make a geothermal evaluation of the two groundwater constrictions.

3.2 Data Collection

The following is a summary of the data sets used in this geothermal evaluation:

1. Geothermal gradient logging. Ten suitable boreholes have been logged (see Table 3-1, Figures 3-1 through 3-4, and Appendix A). An additional nine boreholes (see Table 3-2, Figures 3-5 and 3-6, and Appendix B) have been logged by the staff of LANL (Hunter, 1983). Finally, five detailed temperature logs have been taken from Shearer and Reiter (1978) to bring the

* The principal author of Chapter 3 is Dr. Chandler A. Swanberg, Associate Professor of Physics and Earth Sciences, New Mexico State University.

Table 3-1. Summary of borehole data collected near the La Bajada and Embudo Constrictions in northern New Mexico. The data were collected by R. Sanders and D. Cravens.

<u>Number</u>	<u>Well Name</u>	<u>Location</u>	<u>Coordinates</u>	<u>Depth Range (m)</u>	<u>Temperature Gradient (°C/km)</u>
1	Cravens #1	Taos Junction	25N.10E.29.144	50-180	39.4
2	Eckberg #1	Sombrillo	20N.9E.18.444	45-75	6.5*
3	Eckberg #2	Page	20N.7E.19.221	295	35.9**
4	Cravens-P	Carson	24N.11E.9.412	65	12.1*, **
5	Cravens-K	San Ildefonso	19N.8E.2.240	115-150	21.3
6	Cravens-D	Velarde	22N.9E.10.321	8	--
7	Packey Well	Caja Del Rio	17N.8E.29.121	85-135 140-185	43.2 30.5
8	Rim Well	Caja Del Rio	16N.7E.4.322	40-50	48.0
9	Cravens #2	Velarde	22N.9E.10.122	15-40	26.8
10	S-R #1	Dixon	23N.11E.17.311	70-140	39.4

*Disturbed gradient.

**Gradient calculated using an assumed mean air temperature.

Figure 3-1. Temperature-depth curves for the Cravens#1 and Eckberg#1 boreholes.

Figure 3-2. Temperature-depth curves for the Eckberg #2 and Craves-P boreholes.

Figure 3-3. Temperature-depth curves for the Cravens-K and Packey Well boreholes.

Figure 3-4. Temperature-depth curves for the Rim Well, Cravens#2, and S-R#1 boreholes.

Table 3-2. Summary of borehole data for wells located near the La Bajada and Embudo constrictions in northern New Mexico. The data were collected by Jim Hunter of the Los Alamos National Laboratory.

Well Number	Well Name	Location	Coordinates	Depth Range (m)	Temperature Gradients (°C/km)
1	LANL #1	Page	20N.7E.8.133	100-160 180-320 340-390	30.0 48.2 22.3
2	LANL #2	Espanola	20N.9E.1.442	40-100 105-150 180-205	47.3 55.3 67.2
3	LANL #3	Ojo Caliente	24N.8E.24.233	--	--
4	LANL #4	Pojoaque	19N.9E.8.131	50-56	40.0
5	LANL #5	Jaconita	19N.8E.11.431	--	--
6	LANL #6	Espanola (6 mi E)	20N.10E.8.300	28-44	37.5
7	LANL #7	Penasco	22N.12E.5.144	--	--
8	LANL #8	Ojo Caliente	24N.8E.24.233	4-16	68.39
9	LANL #9*	Page	20N.7E.19.221	150-285	65.5

*Well LANL #9 and Ekberg #2 are reported to be the same well.

Figure 3-5. Temperature-depth curves for the LANL#1, LANL#2, and LANL#9 boreholes.

Figure 3-6. Temperature-depth curves for the LANL#3 through LANL#8 boreholes.

total number of detailed thermal logs to 24 in the immediate vicinity of the two constrictions.

2. Bottom-hole temperature gradients from oil and gas wells. A regional trend surface map based on oil and gas temperature data has been prepared by Morgan et al. (1983) for northwest New Mexico, but this map does not extend into the study area. There are too few oil and gas wells (i.e., a total of four) in the vicinity of the groundwater constrictions to attempt any meaningful geothermal interpretations on the basis of this data set.
3. Temperatures from groundwater wells and springs. A search of the hydrology literature has revealed the presence of five wells and 36 springs in the general vicinity of the two constrictions. Of these, only the single warm well and the 27 tepid springs located within the La Bajada constriction pertain directly to the present study. The possible significance at Ponce de Leon Hot Springs is discussed in the following section.
4. Geochemical data. This data set is basically the same as the spring and well temperature data set. A summary of the geochemical data is given in Table 3-3 for the La Bajada constriction. There are no data available for the Embudo constriction.

3.3 Discussion

3.3.1 Embudo Constriction

The thermal data within and adjacent to the Embudo constriction are shown in Figure 3-7. Several of the well logs show clear disturbances from shallow groundwater circulation and the undisturbed wells have temperature gradients in the range of 30 to 40°C/km. While these undisturbed gradients are high with respect to the world mean, these values are only slightly above the mean for the Rio Grande Rift, and none of the gradients reflect an obvious geothermal target. One of the wells, however, has a heat flow of 229 mWm⁻², or four times the world modal heat flow, and this well represents the most encouraging geothermal indication.

Table 3-3. Summary of geochemical data from the La Bajada constriction.

Number of Samples	Actual Temperatures (°C)	Silica Geotemperatures (°C)	Na-K-Ca Geotemperatures (°C)	Reference
27	16-23	80-120	-	Purtymun et al.
3	18-20	113-119	24-32	Goff et al.

Figure 3-7. Temperature gradients observed near the La Bajada and Embudo constrictions in northern New Mexico.

The geothermal potential of the Embudo constriction is more clearly revealed when examined in the context of the deep sedimentary basin map (Morgan et al., 1983). This map shows that the San Luis Basin terminates at the Embudo constriction; however, the deep part of the San Luis Basin terminates roughly 20 kilometers to the northeast at a place very near the Ponce de Leon Hot Springs. This observation raises the possibility of vertically-stratified aquifers in the San Luis Basin, that is, the deepest aquifers, and those most likely to generate a geothermal anomaly at a basin constriction, may exit the San Luis Basin near Ponce de Leon Hot Springs. Such an occurrence would certainly explain the existence of the Ponce de Leon Hot Springs and also explain the very high heat flow (229 mWm^{-2}) to the southwest of the hot springs. In this context, the Embudo constriction, as defined on the basis of shallow hydrological data, would involve only shallow aquifers and, thus, explain both the disturbed temperature profiles in several of the wells near the constriction and the apparent lack of obvious geothermal activity at the constriction.

3.3.2 La Bajada Constriction

The thermal data within and adjacent to the La Bajada constriction are shown in Figure 3-7, and the geochemical data are summarized in Table 3-3. The temperature gradients typically fall in the 40 to 50 $^{\circ}\text{C}/\text{km}$ range, and this range is high even for the Rio Grande Rift. Furthermore, two of the wells have temperature gradients as high as 65 $^{\circ}\text{C}/\text{km}$, and 27 tepid springs have been observed within the constriction (Purtymun et al., 1980). Despite these positive indications, the

available data do not clearly delineate a geothermal prospect. The wells with the highest temperature gradients do not correlate either with one another or with the tepid spring area. Furthermore, none of the tepid springs exhibit any geochemical evidence of geothermal activity. On the basis of these data, it must be concluded that the La Bajada constriction involves primarily shallow aquifers and the geothermal area, if it exists at all, is located outside the study area.

Finally, the most geothermally promising data presented in Figure 3-7 and Appendices A and B are those from the Ojo Caliente constriction. This area, which is a well known geothermal location, has not been included in this study.

3.4 References

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APPENDIX A

Temperature-Depth Data for Wells Located near the
Embudo and La Bajada Constrictions, Northern New
Mexico.

Note: The data were collected by the staff of the
New Mexico State University Physics Department.

Well Name: Cravens #1

Location, Taos Junction; coordinates, 25N.10E.29.144; depth, 180 meters; inclination, vertical; borehole condition, air; date logged, 6/82; logging system, NMSU Probe.

<u>Depth (m)</u>	<u>Temperature (°C)</u>
5	12.8
10	12.8
15	12.9
20	12.9
25	12.9
30	12.9
35	13.0
40	13.1
45	13.3
50	13.4
55	13.5
60	13.7
65	13.9
70	13.9
75	14.0
80	14.3
85	14.5
90	14.6
95	14.8
100	15.0
105	15.1
110	15.3
115	15.5
120	15.6
125	15.7
130	15.7
135	15.8
140	15.6
145	18.4
150	15.5
155	17.3
160	17.6
165	17.9
170	18.1
175	18.3
180	18.5

Well Name: Eckberg #1

Location, Sombrillo, On Hwy 84 2-1/2 mi S of junction 399; coordinates, 20N.9F.18.444; depth, 80 meters; inclination, vertical; borehole condition, groundwater at ~20 meters; date logged, 7/82; logging system, NMSU Probe.

Depth (m)	Temperature (°C)
20	14.00
25	14.78
30	15.05
35	15.51
40	15.95
45	16.16
50	16.17
55	16.20
60	16.22
65	16.25
70	16.32
75	16.34
80	16.34

Well Name: Eckberg #2

Location, Page, NM; coordinates, 20N.7E.19.221; depth, 295 meters;
inclination, vertical; borehole condition, groundwater at ~275 meters;
date logged, 9/19/82; logging system, NMSU Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
275	23.15
280	23.30
285	23.39
290	23.39
295	23.39

Well Name: Cravens-P

Location, Carson; coordinates, 24N.11E.9.412; depth, 70 meters;
inclination, vertical; borehole condition, groundwater at ~65 meters;
date logged, 8/82; logging system, NMSU Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
65	13.79
70	13.78

Well Name: Cravens-K

Location, San Ildefonso; coordinates, 19N.8E.2.240; depth, 150 meters;
inclination, vertical; borehole condition, groundwater at ~30 meters;
date logged, 7/82; logging system, NMSU Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
30	15.02
35	14.95
40	14.59
45	14.61
50	14.62
55	14.65
60	14.66
65	14.71
70	14.72
75	14.76
80	14.78
85	14.80
90	14.83
95	14.99
100	15.30
105	15.29
110	15.52
115	15.71
120	15.87
125	15.99
130	16.09
135	16.18
140	16.24
145	16.40
150	16.49

Well Name: Cravens-D

Location, Velarde; coordinates, 22N.9E.10.321; depth, 8 meters;
inclination, vertical; borehole condition, groundwater at ~8 meters;
date logged, 8/82; logging system, NMSU Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
8	14.9

Well Name: Packey Well

Location, Caja Del Rio; coordinates, 17N.8E.29.121; depth, 185 meters;
inclination, vertical; borehole condition, groundwater level unknown;
date logged, 3/82; logging system, NMSU Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
5	17.65
10	17.15
15	15.50
20	14.98
25	14.96
30	15.01
35	15.15
40	15.31
45	15.56
50	15.88
55	16.13
60	16.13
65	16.62
70	17.02
75	17.40
80	17.67
85	17.87
90	18.06
95	18.22
100	18.41
105	18.60
110	18.86
115	19.18
120	19.40
125	19.54
130	19.68
135	20.02
140	20.30
145	20.49
150	20.65
155	20.81
160	20.94
165	21.06
170	21.23
175	21.43
180	21.59
185	21.65

Well Name: Rim Well

Location, Caja Del Rio; coordinates, 16N.7E.4.322; depth, 50 meters;
inclination, vertical; borehole condition, groundwater level unknown;
date logged, 2/82; logging system, NMSU Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
5	19.69
10	17.86
15	16.34
20	15.46
25	14.95
30	14.73
35	14.75
40	14.83
45	15.09
50	15.31

Well Name: Cravens #2

Location, Valarde; coordinates, 22N.9E.10.122; depth, 40 meters;
inclination, vertical; borehole condition, groundwater level unknown;
date logged, 6/28/82; logging system, A-Probe NMSU.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
3.0	14.20
6.1	14.00
9.1	14.60
12.1	14.59
15.2	14.83
18.2	14.95
21.3	15.02
24.3	15.18
27.4	15.25
30.4	15.32
33.5	15.37
36.5	15.37
39.6	15.56

Well Name: S-R #1

Location, Dixon; coordinates, 23N.11E.17.311; depth, 140 meters;
inclination, vertical; borehole condition, groundwater level unknown;
date logged, 8/82; logging system, NMSU Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
30	11.59
40	12.07
50	12.63
60	13.15
70	13.63
80	14.04
90	14.49
100	14.90
110	15.27
120	15.63
130	16.03
140	16.40

APPENDIX B

Temperature-Depth Data for Wells Located near the
Embudo and La Bajada Constrictions, Northern New
Mexico.

Note: The data were collected by the staff of the
Los Alamos National Laboratory.

Well Name: LANL #1

Location, Page; coordinates, 20N.7E.8.133; depth, 390 meters;
inclination, vertical; logging system, LANL Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
20	12.34
40	13.20
60	13.84
80	14.74
100	15.46
120	16.05
140	16.68
160	17.25
180	18.04
200	19.27
220	20.41
240	21.39
260	22.36
280	23.27
300	24.07
320	24.79
340	25.54
360	25.97
380	26.47
390	26.63

Well Name: LANL #2

Location, Espanola; coordinates, 20N.9E.1.442; depth, 207 meters;
inclination, vertical; logging system, LANL Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
10	13.40
15	13.53
20	13.69
25	13.79
30	13.98
35	14.81
40	14.38
45	14.55
50	14.78
55	15.07
60	15.22
65	15.45
70	15.69
75	16.03
80	16.27
85	16.41
90	16.58
95	16.92
100	17.21
105	17.62
110	17.97
115	18.29
120	18.45
125	18.82
130	19.09
135	19.35
140	19.58
145	19.84
150	20.19
155	20.38
160	20.42
165	20.42
170	21.02
175	21.35
180	21.48
185	21.77
190	22.11
195	22.48
200	22.85
205	23.11
207	23.52

Well Name: LANL #3

Location, Ojo Caliente; coordinates, 24N.8E.24.233; depth, 26.3 meters;
inclination, vertical; date logged, 11/17/81.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
1.3	52.76
3.3	53.90
5.3	54.42
7.3	54.63
9.3	54.76
11.3	54.79
13.3	54.82
15.3	54.88
17.3	54.88
19.3	54.89
21.3	54.91
23.3	54.94
25.3	54.95
26.3	54.63

Well Name: LANL #4

Location, Pojoaque; coordinates, 19N.9E.8.131; depth, 55.7 meters;
inclination, 92°; date logged, 3/31/82.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
2	10.83
4	11.53
6	13.00
8	13.67
10	13.75
12	13.75
14	13.64
16	13.57
18	13.56
20	13.65
22	13.82
24	13.97
26	14.06
28	14.06
30	14.12
32	14.12
34	14.16
36	14.16
38	14.19
40	14.24
42	14.25
44	14.25
46	14.28
48	14.30
50	14.40
52	14.48
54	14.56
55.7	14.56

Well Name: LANL #5

Location, Jaconita; coordinates, 19N.8E.11.431; depth 39 meters;
inclination, vertical; date logged, 1/6/82; logging system, LANL Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
9	14.32
10	14.32
12	14.32
14	14.32
16	14.32
18	14.27
20	14.19
22	14.08
24	14.05
26	14.04
28	14.05
30	14.07
32	14.08
34	14.10
36	14.14
38	14.19
39	14.27

Well Name: LANL #6

Location, Espanola (6 mi E); coordinates, 20N.10E.8.300; depth, 45 meters;
inclination, vertical; date logged, 4/8/82; logging system, LANL Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
9	10.68
10	10.66
12	10.76
14	10.84
16	10.92
18	10.97
20	11.01
22	11.06
24	11.08
26	11.12
28	11.27
30	11.34
32	11.40
34	11.48
36	11.56
38	11.64
40	11.70
42	11.80
44	11.86
45	11.92

Well Name: LANL #7

Location, Penasco; coordinates, 22N.12E.5.144; depth, 35 meters;
inclination, vertical; logging system, LANL Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
1	8.72
2	8.70
3	8.82
4	9.04
5	9.22
6	9.42
7	9.54
8	9.60
9	9.71
10	9.78
11	9.77
12	9.82
13	9.90
14	10.15
15	10.22
16	10.27
17	10.27
18	10.28
19	10.27
20	10.27
21	10.26
22	10.30
23	10.34
24	10.32
25	10.34
26	10.32
27	10.32
28	10.31
29	10.34
30	10.40
31	10.34
32	10.34
33	10.31
34	10.26
35	10.36

Well Name: LANL #8

Location, Ojo Caliente; coordinates, 24N.8E.24.233; depth, 66 meters;
inclination, vertical; logging system, LANL Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
2	12.09
4	13.27
6	13.48
8	13.64
10	13.74
12	13.85
14	14.00
16	14.13
16.7	14.81

Well Name: LANL #9

Location, Page; coordinates, 20N.7E.19.221; depth, 286 meters;
inclination, vertical; logging system, LANL Probe.

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>
30	9.8
60	11.4
90	12.3
120	13.4
150	14.5
180	16.0
210	18.2
240	20.1
265	21.9
270	22.1
275	22.2
280	23.0
285	23.1
286	23.3

4.0 Thermal Data for Springs and Wells*

4.1 Compiled Data

This Chapter 4 consists of thermal and dissolved silica content data for springs and shallow groundwater wells. The data (see Table 4-1) have been compiled from the USGS water quality file (WATSTORE) but have not been field checked and may contain errors. Figure 4-1 contains the data of Table 4-1, Shearer and Reiter (1978), and field measurements obtained as part of this study.

4.2 Reference

Shearer, C., and Reiter, M., 1978, Basic heat flow data in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-File Report 93, 375 pp.

* The material contained in Chapter 4 was compiled by Dr. Chandler A. Swanberg, Associate Professor of Physics and Earth Sciences, New Mexico State University.

Table 4-1. Spring and well data for north central New Mexico. The data have been compiled from the USGS WATSTORE file.

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
04N.02E.08.243	W	38	13.5	-
04N.02E.11.211	W	439	23.5	-
04N.02E.35.223	W	187	23	-
Antonio Sedillo Grant	S	-	19	13
Antonio Sedillo Grant	S	-	30	-
Antonio Sedillo Grant	S	-	24	32
Antonio Sedillo Grant	S	-	22	20
Antonio Sedillo Grant	S	-	18.5	28
Antonio Sedillo Grant	S	-	14.5	-
Antonio Sedillo Grant	S	-	24	22
Antonio Sedillo Grant	S	-	16.5	30
Antonio Sedillo Grant	S	-	13.5	22
Antonio Sedillo Grant	S	-	14.0	23
Antonio Sedillo Grant	S	-	13.5	32
Antonio Sedillo Grant	S	-	11.5	27
Antonio Sedillo Grant	S	-	21.5	23
Antonio Sedillo Grant	S	-	23.0	12
04N.03W.06.433	S	-	20.0	25
04N.18W.28.211	S	-	13.0	11
05N.01E.13.332	W	519	20.5	31
05N.01E.28.114	W	393	22.0	24
05N.01W.14.231	W	99	18.0	17
05N.01W.32.423	W	412	22.0	21
05N.03E.11.331	W	296*	16.5	-
05N.03W.34.200	W	80	15.5	-
05N.04E.03.114	W	42	11.0	17
05N.04E.09.122	W	250	19.0	19
05N.05W.10.300	W	160	18.0	14
05N.05W.10.333	W	200	18.0	14
05N.05W.26.100	W	623	19.0	11
05N.07W.34.433	S	-	19.0	23
05N.10W.12.134	S	-	14.0	27
05N.16W.36.431	S	-	11.0	17
05N.19W.07.334	S	-	13.0	27
05N.20W.24.122	W	180	15.0	27
05N.20W.29.344	W	1,450	23.0	15
06N.01E.33.433	W	556	20.7	24
06N.01W.29.130	W	567	18.8	17
06N.02W.13.234	W	133	18.0	22
06N.03E.07.240	W	295	20.7	41
06N.20W.14.000	W	200	11.5	-
06N.21W.10.222	W	270	18.0	20

Table 4-1 (continued).

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
07N.01W.23.334	W	576	16.2	26
07N.01W.31.122	W	97	18.0	27
07N.02E.07.11414A	W	16,300	32.5	58
07N.02E.26.112	W	80	15.0	35
07N.02E.26.314	W	58	15.5	-
07N.02E.28.234	W	165	18.5	51
07N.02E.28.243	W	400	18.0	50
07N.03E.25.220	W	655	23.0	26
07N.04W.03.43	S	-	18.5	-
07N.04W.11.431	S	-	16.5	20
07N.05W.20.34	S	-	20	-
07N.20W.14.213	W	103	15.5	10
08N.01W.24.312	W	685*	21.5	29
08N.02E.01.342	W	430	20.0	44
08N.10W.24.311	W	555	20.0	14
08N.15W.27.342	W	465	18.0	-
08N.17W.02.314	W	1,180	23.0	-
08N.19W.04.321	W	590	18.0	-
08N.19W.12.211	W	1,120	18.0	-
08N.19W.22.313	W	500	22.0	-
08N.20W.04.344	W	515	18.0	-
08N.20W.01.322	S	-	13.5	16
08N.20W.08.433	S	-	9.5	-
08N.20W.20.2112	S	-	28.0	14
08N.20W.20.4222	S	-	22.0	14
08N.20W.21.1441	S	-	22.5	14
08N.21W.12.312	W	71	11.0	-
08N.21W.26.321	W	15	22.0	-
09N.03W.20.414	W	250	21.5	-
09N.06W.31.130	W	41	14.5	21
09N.12W.02.241	S	-	8.0	-
09N.14W.06.400	W	225	24.0	29
10N.06W.21.400	S	-	11.0	51
10N.06W.31.443	W	145	20.0	36
10N.06W.35.300	W	125	16.0	24
10N.06W.35.322	W	120	16.0	29
10N.06W.35.342	W	122	16.0	24
10N.07W.18.331	W	430	15.5	-
10N.07W.20.411	S	-	8.5	-
10N.07W.29.214	W	236	13.5	60
10N.07W.31.400	W	145	14.5	36
10N.07W.35.210	W	132	15.5	27
10N.07W.36.322	W	154	15.5	-

Table 4-1 (continued).

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
10N.08W.28.314	W	125	15.0	21
10N.08W.30.244	W	170	15.0	-
10N.09W.06.442	S	-	10.5	41
10N.09W.23.134	W	1,040	16.0	8.4
10N.09W.23.423	S	-	61.0	30
10N.09W.25.244	W	165	14.5	-
10N.09W.25.400	W	70	14.5	18
10N.10W.03.423	S	-	16.0	-
10N.10W.03.433A	W	130*	1.6	20
10N.10W.03.433B	W	148	18.0	18
10N.10W.26.331	W	216	17.0	21
10N.11W.17.231	S	-	4.5	-
11N.05W.30.420	W	466	19.0	15
11N.05W.30.422	W	466	19.0	15
11N.05W.32.234	W	79	13.0	42
11N.10W.04.433	W	150	15.0	25
11N.10W.04.333	W	150	15.0	25
11N.10W.04.333	W	198	21.5	-
11N.10W.05.212	W	136	13.5	-
11N.10W.02.122	W	120	15.5	-
11N.10W.08.222	W	165	13.5	-
11N.10W.08.343	W	86	16.5	-
11N.10W.09.221	W	480	13.0	-
11N.10W.16.121	W	155	12.8	-
11N.10W.16.1212	W	180	13.5	-
11N.10W.21.242	W	90	16.5	-
11N.10W.22.311	W	140	16.5	-
11N.10W.26.321B	W	245	19.5	-
11N.10W.26.321C	W	245	22.5	-
11N.10W.27.232	W	250*	16.5	20
12N.07W.11.2121	S	-	7.0	30
12N.09W.08.431	W	98	14.5	-
12N.10W.05.341A	W	725	19.5	-
12N.10W.08.300	W	250*	19.0	19
12N.10W.23.233	W	285	20.0	-
12N.10W.23.233	W	130*	20.5	-
12N.10W.26.242	W	971	20.0	16
12N.10W.27.244	W	371	14.0	-
12N.10W.27.431	W	490	15.0	-
12N.10W.27.4311	W	584	15.0	-
12N.10W.29.434	W	152	13.0	-
12N.10W.29.434	W	205	13.0	-
12N.10W.29.434A	W	398	13.0	-

Table 4-1 (continued).

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
12N.10W.30.412	W	225	13.5	-
12N.10W.33.444	W	195	13.0	-
12N.10W.33.444	W	150	13.0	-
12N.10W.34.2141	W	275	13.5	-
12N.10W.34.412	W	978	13.0	-
12N.11W.10.4312	W	500	15.0	-
12N.11W.14.213	W	115	14.0	24
12N.11W.14.213	W	150	19.0	24
12N.11W.14.311A	W	130	14.0	-
12N.11W.15.211	W	450	14.5	-
12N.11W.24.233	W	386	14.5	-
12N.11W.24.411	W	360	13.5	15
12N.11W.24.411	W	357	14.5	15
12N.11W.25.213	W	236	14.0	-
12N.12W.04.224	S	-	13.0	-
13N.04W.31.114	W	250	14.5	26
13N.08W.24.334B	W	200	13.5	11
17N.10E.09.32244A	W	560	14.5	19
18N.09E.24.344	S	-	12.0	20
19N.07E.14.312	W	2,030	28.5	34
19N.07E.20.341	W	2,500	28.0	74
19N.07E.22.131	S	-	11.0	30
19N.07E.36.13343	W	1,090	23.5	38
19N.08E.06.4224	W	40	13.5	18
19N.08E.08.243	W	70	13.5	32
19N.08E.10.321	W	63	6.5	26
19N.08E.12.411	W	80	11.0	22
20N.09E.05.422	W	150	12.0	51
Mora Grant	S	-	7.0	25
13N.26E.8.421	W	1,780	25.0	12
21N.21E.20.213	S	-	13.5	29
Polvadera Grant	S	-	16.0	2.2
20N.08E.03.220	W	150	13.5	24
20N.08E.22.110	W	45	11.0	35
20N.09E.01.220	W	63	10.0	26
21N.02E.14.433	S	-	10.5	10
22N.03E.22.111	S	-	11.0	19
23N.03W.11.3332	W	153	13.0	17
23N.05W.01.232	W	198	11.0	8.1
24N.01E.07.142	W	26	10.5	-
24N.01E.30.441	W	42	13.5	0
24N.02W.16.444	W	753	13.5	8.0
24N.07E.26.122	S	-	18.5	35

Table 4-1 (continued).

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
24N.08E.25.313	W	53	21.5	39
25N.01W.08.111	W	152	10.0	11
25N.02W.11.141	W	130	11.0	-
25N.02W.23.441	W	170	10.0	-
25N.04E.02.434	S	-	20.0	15
25N.06E.00.000	S	-	15.0	15
25N.06E.03.220	S	-	11.5	11
25N.08E.26.414	S	-	36.0	22
25N.08E.98.314	S	-	19.0	-
26N.01E.17.330	S	-	7.0	11
26N.01E.33.314	S	-	9.0	15
26N.03W.07.314	W	370	11.0	17
26N.06E.28.134	S	-	9.5	9.3
26N.09E.24.143	W	750*	20.0	85
27N.04W.30.1222	S	-	14.5	12
27N.08E.04.424	S	-	11.5	9.1
28N.07E.06.321	S	-	11.5	19
28N.07E.28.132	S	-	12.0	51
28N.09E.31.330	S	-	17.0	32
29N.04W.19.412	S	-	13.0	9.1
29N.06W.35.200	W	365	14.5	19
29N.07E.12.212	S	-	11.0	43
29N.08E.29.441	S	-	9.0	48
31N.03E.13.334	W	690	14.5	8.1
31N.07E.01.222	W	16	15.0	40
32N.07E.28.231	S	-	8.5	36
Antonio Martinez or Godo	S	-	38.0	60
Gijosa Grant Rio Grande	S	-	17.0	30
Ojo Caliente Grant Iron	S	-	40.0	-
Rancho Del Rio Grande	S	-	32.0	54
Sangre De Cristo Grant	W	250	11.0	23
24N.09E.11.124	W	650	22.0	64
25N.11E.28.343	W	384	19.0	50
25N.13E.08.4341	W	204	12.5	18
26N.11E.21.211	W	700*	13.0	53
27N.11E.26.333	W	400	25.5	60
27N.11E.35.311	W	800	23.5	52
27N.12E.31.311	S	-	37.0	67
28N.12E.01.113	W	78	10.0	23
28N.12E.01.114	W	70	8.5	18
28N.12E.01.121	W	30	0.5	18
28N.12E.01.131	W	45	8.0	22
28N.12E.01.131	W	22	8.0	24

Table 4-1 (continued).

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
28N.12E.01.133	S	-	8.5	17
28N.12E.03.441	S	-	17.0	32
28N.12E.08.	S	-	17.0	33
28N.12E.08.142	S	-	18.0	32
28N.12E.09.243	S	-	16.5	32
28N.12E.17.2111	S	-	14.5	34
28N.12E.9.22	S	-	11.5	-
Caja Del Rio Grant	S	-	21.0	-
Caja Del Rio Grant	S	-	21.5	-
La Majada Grant	S	-	12.5	13
Santa Fe Nat. Forest	S	-	9.0	32
Santa Domingo De Cundiyo	S	-	8.5	17
10N.07E.09.444	W	340	14.5	20
10N.07E.27.12113	W	327	15.5	14
10N.08E.35.4241	W	250	14.5	-
10N.09E.05.1113	W	325	14.5	25
10N.09E.15.423	W	90	13.5	-
10N.09E.18.114	W	192	15.0	23
10N.09E.19.122	W	140	13.5	-
10N.09E.20.444	W	95	13.5	22
10N.09E.21.431	W	101	13.0	-
10N.09E.26.442	W	130	15.0	-
10N.09E.33.11213	W	200	14.0	-
10N.10E.21.322	W	310	15.0	-
10N.11E.25.3333	W	110	14.5	18
11N.07E.21.322	W	160	15.0	28
11N.07E.26.24231	W	300	17.0	25
11N.09E.28.41421	W	210	16.0	25
11N.10E.16.3131	W	140	14.5	19
12N.10E.34.113	W	400	16.0	20
12N.11E.29.423	W	620	12.0	16
14N.08E.02.3243	W	114	17.0	25
15N.08E.05.11414	S	-	18.0	28
15N.08E.07.32334	W	272	12.5	40
15N.10E.12.22243	W	62	14.5	19
16N.08E.01.32114	W	380	14.0	19
16N.08E.24.333	W	225	17.0	24
16N.08E.32.3413	W	163	15.0	28
16N.09E.01.43311	W	300	14.0	30
17N.08E.25.32431	W	440	16.0	19
17N.09E.23.332	W	347	11.5	-
17N.09E.27.143	W	20	15.0	17
17N.09E.27.232	W	740	24.0	18
17N.09E.32.32142	W	110	13.5	13

Table 4-1 (continued).

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
29N.09E.11.320	W	1,300	29.5	58
30N.12E.01.144	W	155	10.0	-
30N.12E.01.342	W	196	11.5	25
01N.02E.34.130	W	104	10.0	18
01N.04W.24.442	W	>190	22.5	37
01S.01E.23.313	W	45	17.0	-
01S.01W.14.431	W	35	20.0	-
01S.01W.22.200	W	100	20.0	50
01S.01W.22.324	W	177	21.0	-
01S.01W.23.122	W	38	20.0	-
01S.01W.23.231	W	75	21.0	-
01S.01W.23.331B	W	54	18.0	-
01S.01W.23.333	W	28	18.0	-
01S.01W.23.431	W	100	16.5	38
10S.01W.26.200	W	60	18.5	53
01S.01W.26.200B	W	125	18.0	41
01S.01W.27.242	W	35	17.0	-
01S.01W.27.400	W	100	9.0	31
01S.01W.27.434	W	80	18.0	-
01S.01W.27.442	W	60	19.0	-
01S.01W.34.422	W	160	20.0	-
01S.01W.35.142	W	130	19.0	-
01S.02W.30.121	W	280	18.0	-
01S.03W.31.433	W	390	19.0	-
01S.08E.04.323	W	637	20.0	-
02S.01W.02.344A	W	80	18.0	-
02S.01W.02.434	W	50	15.5	-
02S.01W.10.221	W	210	21.5	30
02S.01W.11.114	W	140	21.0	-
02S.01W.11.124	W	87	17.0	-
02S.01W.11.222	W	25	18.0	-
02S.01W.13.113	W	104	15.5	33
02S.01W.13.134	W	145	17.0	-
02S.01W.13.311	W	40	17.0	-
02S.01W.22.141	W	254	23.0	-
02S.01W.24.121	W	20	17.0	-
02S.01W.24.423	W	33	18.0	-
02S.01W.24.431	W	22	18.0	-
02S.01W.25.122	W	52	20.0	-
02S.01W.25.344	W	40	19.0	-
02S.01W.35.200	W	200	18.8	33
02S.01W.35.221	W	180	19.0	-
02S.01W.36.111	W	110	19.0	-

Table 4-1 (continued).

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
02S.01W.36.134	W	105	20.0	-
02S.01W.36.214	W	42	18.0	-
02S.01W.36.312	W	80	20.0	-
02S.01W.36.314	W	90	22.0	-
02S.01W.36.433	W	60	19.0	-
02S.02E.03.111	W	10	16.0	22
02S.02W.18.112	W	150	19.0	-
02S.02W.34.432	W	134	18.0	-
02S.03W.01.322	W	160	22.0	-
02S.03W.07.433	W	325	20.0	-
02S.03W.22.114	W	315	21.0	-
02S.03W.25.113	W	280	19.0	-
02S.03W.27.223	W	420	22.0	-
02S.04W.12.341	W	158	17.0	-
02S.04W.26.342	W	240	18.0	24
02S.04W.26.344	W	180	18.0	23
03N.01W.21.331	W	405	19.0	23
03N.02E.27.123	W	380	17.0	44
03N.02E.31.431	W	135	22.5	56
03N.02E.33.222	W	320	17.5	30
03N.03E.16.410	W	400	19.0	-
03N.04E.28.244	W	192	15.5	16
03S.01E.06.000	W	50	18.5	28
03S.01E.20.400	W	150	18.0	30
03S.01E.23.11	W	395	23.0	39
03S.01E.30.100	W	90	12.5	30
03S.01W.01.122	W	85	22.0	-
03S.01W.02.241A	W	63	19.0	-
03S.01W.02.300B	W	101	18.0	29
03S.01W.02.400	W	100	16.9	39
03S.01W.02.414A	W	50	18.0	-
03S.01W.02.432	W	70	23.0	-
03S.01W.10.200	W	185	20.7	45
03S.01W.11.100	W	118	19.0	30
03S.01W.11.114	W	70	17.0	28
03S.01W.11.200	W	120	18.0	31
03S.01W.11.300	W	115	18.5	31
03S.01W.11.314A	W	115	18.0	31
03S.01W.11.314B	W	119	18.0	34
03S.01W.11.332A	W	112	18.0	31
03S.01W.11.344	W	66	18.5	34
03S.01W.13.122	W	87	20.0	-
03S.01W.13.212	W	21	15.3	35

Table 4-1 (continued).

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
03S.01W.13.213	W	117	18.0	-
03S.01W.13.243A	W	52	21.0	-
03S.01W.13.400A	W	100	15.4	29
03S.01W.13.411	W	74	20.0	-
03S.01W.14.122	W	62	18.5	34
03S.01W.14.300	W	300	19.0	39
03S.01W.14.311	W	140	18.0	-
03S.01W.14.400A	W	130	18.5	45
03S.01W.14.400B	W	225	21.0	40
03S.01W.15.3114	S	-	22.5	26
03S.01W.16.300	W	300	32.4	26
03S.01W.16.323	W	300	31.8	26
03S.01W.21.000	W	130	23.0	33
03S.01W.22.112	S	-	30.0	28
03S.01W.22.1131	S	-	29.0	27
03S.01W.22.131	S	-	30.0	26
03S.01W.24.400B	W	113	15.5	30
03S.01W.27.300A	W	285	20.0	38
03S.01W.33.143	W	24	17.0	45
03S.02E.08.422	S	-	9.0	19
03S.02E.19.314	S	-	24.0	19
03S.02W.20.111	W	540	22.0	-
03S.02W.36.212	W	155	23.0	-
03S.03E.05.2132	W	315	19.0	12
03S.03W.10.311	S	-	16.5	-
03S.03W.20.421	S	-	12.0	19
03S.03W.21.344	S	-	8.5	22
03S.03W.27.212	S	-	11.0	23
03S.03W.27.441	S	-	9.0	22
03S.03W.33.442	S	-	8.0	16
03S.04W.24.242	S	-	16.0	19
03S.06W.11.241	W	291	21.0	32
04N.01W.15.211	W	268	21.0	15
04N.01W.28.323	W	260	20.5	15
04N.02W.02.433	W	439	18.5	53
04N.03W.25.334	S	-	16	24
04N.03W.35.211	S	-	6.5	22
04S.01E.19.242	W	47	22.0	35
04S.02W.03.321	W	115	21.0	-
04S.02W.12.112	W	300	19.0	-
04S.03W.06.442	S	-	10.0	16
04S.03W.08.241	S	-	10.0	17
*05S.01E.04.122	W	100	19.5	44

Table 4-1 (continued).

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
05S.01E.17.344	W	149	16.5	31
05S.01E.17.344	W	125	17.0	32
05S.01E.30.133	W	65	22.5	46
05S.01E.30.241	W	142	17.0	40
05S.01W.11.132	W	550	19.0	45
05S.02E.02.130	W	55*	11.5	-
05S.02E.16.323	W	280	19.0	-
05S.03E.09.244	W	352	23.0	1.2
05S.03E.13.200	W	100	16.5	-
05S.05E.14.400	W	315	13.0	-
05S.05E.19.200	W	190*	19.5	-
05S.05E.32.400	W	180	17.0	-
06S.01E.05.233	W	170	16.0	33
06S.01E.07.213	W	100	33.0	24
06S.01E.09.111A	W	200	15.5	35
06S.01E.09.111B	W	500	19.5	-
06S.01E.09.111C	W	500	20.5	-
06S.01E.36.233	W	300	21.0	-
06S.01W.12.231	W	155	24.0	42
06S.02E.01.444A	W	602	24.5	37
06S.02E.04.144	W	700	28.5	-
06S.02E.04.300	W	520	23.5	28
06S.02E.10.141	W	454	25.5	-
06S.02E.28.400	W	>200	24.5	-
06S.03E.05.232	W	752	26.5	32
06S.05W.24.34233	W	400	21.0	36
06S.06E.16.400	W	18	10.0	20
06S.06E.24.400	W	315	25.0	-
06S.06E.26	W	205	14.8	10
06S.06E.26.300	W	67	15.5	11
*06S.06E.31.223	W	7,470	7.0	13
06S.06E.34.200	W	220	18.5	-
06S.06E.34.200	W	52	14.5	10
06S.06E.34.200	W	210	15.0	-
06S.08W.08.432	W	770	35.0	29
07S.01E.27.214A	W	256	23.5	-
07S.01W.18.140	W	140	22.0	33
07S.01W.18.200	W	113	21.0	32
07S.02W.04.334	W	352	25.0	29
07S.03E.04.200	W	160*	21.0	-
07S.04E.23.300	W	130*	19.0	-
07S.04W.27.432	W	359	23.0	46
07S.06E.29.414	S	-	9.5	21

Table 4-1 (continued).

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
07S.07E.15.442	S	-	24.0	20
07S.08E.29.100	W	370	20.0	-
07S.08W.04.344A	W	580	16.0	49
08S.04W.31.441	W	200	24.5	38
08S.04W.33.3211	W	403	24.5	44
08S.05E.32.431	W	240*	21.5	31
08S.05E.08.322A	W	710	20.5	19
08S.07W.31.144	S	-	27.0	38
08S.07W.31.233	S	-	27.0	40
08S.07W.31.244	S	-	27.0	40
08S.07W.31.300	S	-	28.0	42
08S.05W.32.334	W	250	24.4	17
09S.01W.23.311	W	300	24.5	30
09S.01W.23.311	S	-	11.5	-
09S.05E.15.143	W	180*	18.5	-
09S.07W.6.423	S	-	16.0	26
09S.08W.03.213	W	120	14.0	-
12N.01E.22.222	W	1,000*	21.5	-
12N.01W.14.111	W	120	20.0	27
12N.03E.24.423	W	96	15.0	36
12N.03E.27.222	W	70	15.0	34
12N.03E.35.243	W	15	10.5	24
12N.04E.06.213	W	500	18.0	-
12N.05E.25.332	W	285	12.0	-
13N.01W.16.230	W	50	16.0	22
13N.03E.03.223	W	183	16.0	36
13N.04E.01.234	W	550	26.0	-
13N.04E.30.231	W	90	12.0	52
13N.06E.16.213	W	140*	14.5	-
14N.02E.05.320	W	130	14.5	18
14N.03E.18.340	W	130	16.5	32
14N.05E.33.341	W	165	18.5	26
15N.01E.26.222	W	117	16.0	-
15N.03W.12.322	W	1,110	23.5	-
16N.01E.34.44	W	200	17.0	52
16N.01W.01.410	W	550	32.0	18
16N.01W.01.410	W	2,010	54.4	-
16N.04W.18.4444	W	244	16.0	9.8
16N.04W.36.2321	W	602	17.5	14
19N.01W.08.223	W	670	17.0	11
19N.01W.14.3332	W	2,780	16.3	1.8
19N.03E.32.331	W	155	15.0	37
20N.01W.07.32	W	260	16.0	18

Table 4-1 (continued).

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
20N.02W.17.132	W	240	14.5	15
20N.02W.19.124	W	300	12.0	-
20N.02W.31.2	W	7	12.0	22
21N.01W.05.431	W	168	13.5	-
21N.01W.15.321	W	200*	13.5	-
21N.01W.15.322	W	300	13.5	-
21N.01W.20.322	W	85	11.0	14
21N.01W.28.410	W	148	12.0	-
21N.01W.29.200	W	104	11.0	12
21N.01W.29.24	W	86	5.5	17
21N.01W.29.24	W	100	5.5	17
21N.05W.32.424	W	2,450	33.0	14
22N.01W.32.3312	W	300	11.0	-
22N.03W.09.323	W	180	12.0	12
22N.05W.15.334	W	210	9.5	10
22N.05W.15.334	W	180	9.5	10
23N.01W.32.242A	W	34	11.5	-
23N.04W.21.4231	W	550	10.0	9.8
Atrisco GR ABO College 1	W	1,680	28.0	30
Atrisco GR ABO College 2	W	1,580	30.0	30
Atrisco GR ABO College 3	W	1,450	26.0	50
New Atrisco No. 5	W	1,270	32	46
New Mexico Utilities	W	1,360	23.0	66
Ponderosa Num 6	W	1,680	28	-
Walker Well No. 1	W	1,800	27.0	31
Walker Well No. 2	W	1,790	29.0	41
02100221343	W	1,180	31.1	42
02100404221	W	1,330	23.9	26
02100422342	W	1,340	23.3	25
02110335313	W	1,040	17.2	33
02110432333	W	1,090	22.8	30
08N.02E.01.312	W	74	14.0	-
09N.01W.04.424	W	150	15.5	20
09N.02E.03.342	W	140	20.0	-
09N.02E.11.221	W	45	16.5	-
09N.02E.11.212	W	42	15.5	-
09N.02E.35.113	W	115	16.0	-
09N.02E.35.400	W	<35	15.5	37
09N.03E.05.234	W	92	20.5	57
09N.03E.09.113	W	900	25.0	69
09N.03E.11241	W	341	19.5	41
09N.03E.18.434	W	95	21.0	-
09N.03E.19.322	W	72	19.0	-

Table 4-1 (continued).

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
09N.04E.01.A	W	72	15.5	-
09N.04E.01.B	W	80*	16.0	-
09N.04E.24.100	W	8*	19.5	-
09N.04E.35.200A	W	76	16.5	-
09N.06E.12.332	W	186	13.0	-
09N.06E.23.343	W	73	10.5	-
09N.06E.26.333	W	160	15.5	28
10N.01E.30.222A	W	1,350	25.5	15
10N.01E.30.222B	W	1,000	25.5	19
10N.01E.30.222C	W	1,200	25.5	18
10N.01W.18.331	W	275	18.0	21
10N.01W.21.132	W	205	21.5	19
10N.02E.12.412	W	1,000	21.0	64
10N.02E.14.211	W	162	16.0	51
10N.02E.21.343	W	1,180	31.0	42
10N.02E.25.433A	W	36	16.5	-
10N.02E.25.433B	W	37	15.5	-
10N.02W.11.432	W	128	18.5	-
10N.02W.18.100	W	740	18.5	20
10N.02W.18.133	W	570	19.0	-
10N.02W.19.313	W	430	20.0	-
10N.02W.25.432	W	193	20.5	23
10N.02W.28.333	W	135	20.5	-
10N.02W.30.133	W	65	23.5	-
10N.03E.07.242	W	68	16.0	60
10N.03E.17.343	W	520	18.0	61
10N.03E.19.111	W	100	14	33
10N.03E.29.312	W	<40	13.5	-
10N.03E.31.232	W	40	14.5	-
10N.03E.35.241	W	984	16.5	32
10N.03E.36.132	W	997	20.0	38
10N.03W.12.211	W	196	21.0	-
10N.04E.03.223	W	291	24.5	23
10N.04E.04.221	W	1,320	24.0	26
10N.04E.05.122	W	1,220	23.5	32
10N.04E.20.111	W	1,280	21.5	28
10N.04E.21.344	W	1,680	26.5	26
10N.04E.22.342	W	1,340	23.5	25
10N.04E.28.22	W	1,700	25.0	26
10N.04E.34.214	W	1,200	14.3	20
10N.05E.02.242	W	185	12.0	27
10N.05E.02.433	W	42	12.0	-
10N.05E.12.122	W	140	14.5	17

Table 4-1 (continued).

Location	Spring (S) or Well (W)	Well Depth (ft)	Temperature (°C)	SiO ₂ Concentration (mg/l)
10N.05E.14.3241	W	170	13.5	-
10N.05E.26.314	W	96*	11.5	17
10N.05E.30.32241	W	50	16	25
10N.05E.30.32241R	W	75	24.0	-
10N.05E.30.32241	W	60	16.0	-
10N.06E.05.121	W	310	13.0	-
10N.06E.06.3241	W	162	16.0	-
10N.06E.14.424	W	260	13.0	-
10N.04E.25.142	W	91	17.0	-
11N.01W.28.224	W	96	13.9	59
11N.02E.22.441	W	240	20.0	15
11N.03E.09.331	W	>100	14.0	-
11N.03E.10.444	W	160	14.5	-
11N.03E.20.331A	W	44	14.0	-
11N.03E.20.333A	W	35	18.9	-
11N.03E.20.333B	W	<40	14.0	-
11N.03E.20.333C	W	45	14.5	-
11N.03E.20.334A	W	40	15.0	-
11N.03E.20.334B	W	48	15.0	-
11N.03E.23.112	W	300	14.5	28
11N.03E.26.342	W	302	16.0	-
11N.03E.28.113	W	18	15.0	-
11N.03E.28.131	W	45	14.5	-
11N.03E.29.111A	W	45	14.5	-
11N.03E.29.111B	W	42	15.0	-
11N.03E.29.431A	W	55	14.5	-
11N.03E.29.431B	W	<40	15.5	-
11N.03E.30.341	W	110	14.5	-
11N.03E.31.322	W	70	14.5	43
11N.03E.34.141	W	150	16.5	35
11N.03E.35.313	W	1,040	17.0	33
11N.03W.10.123	W	1,100	24.0	11
11N.03W.33.200	W	24	18.5*	12
11N.03W.34.133	W	155	20.5	-
11N.03W.36.224B	W	322	18.0	21
11N.04E.16.341	W	750	20.5	26
11N.04E.31.412	W	1,200	22.0	33
11N.04E.32.100	W	1,540	26.0	30
11N.04E.32.333	W	1,090	23.0	30
11N.05E.24.143	W	198	13.0	-
11N.05E.24.421	W	198	10.5	16
11N.06E.19.313	W	136	14.5	-
11N.06E.36.230	W	1,000	16.0	17

*Estimated data.

Figure 4-1. Temperature data for springs and wells in north central New Mexico.

5.0 Geothermal Resources of the Rio Grande Rift*

5.1 Introduction

Rift systems result as a consequence of extensional tectonics, and currently active rifts have many features in common including concurrent crustal thinning, volcanism and tectonism, deep sedimentary basins, high heat flow, and geothermal resources. However, rift systems are evolutionary in nature and, therefore, their tectonic and magmatic setting may be quite different. These differences may be reflected in the nature of the associated geothermal resources. The basic model for rift evolution has been modified from Elders et al. (1972) and can be summarized as follows. Stage 1 involves regional uplift, lateral expansion, the formation of the major basins, and the subsequent deposition of the alluvial fill. Stage 2 involves the continuing evolution of the near-surface geologic and physiographic features and also the invasion of basaltic magma into the lower crust. These magmas may also be intruded into the intermediate level of the crust or extruded upon the surface. Stage 3, the final stage, occurs as sufficient volumes of basaltic magma are intruded into the crust to raise the regional isotherms above the granite solidus. This condition initiates crustal melting, the formation of rhyolitic volcanoes, and the onset of greenschist metamorphism in the sedimentary pile.

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A highly evolved rift, as represented by stage 3, has undergone sufficient lateral extension and mantle upwarp to initiate crustal melting and the shallow emplacement of rhyolitic plutons. The geothermal resources in such an environment will tend to be high-temperature ($> 200^{\circ}\text{C}$) and be closely associated with the silicic volcanics. The geothermal fluids will generally reflect the magmatic origin of the heat and will be rich in volcanic volatiles such as hydrogen sulfide, mercury, and arsenic. Application of the SiO_2 and Na-K-Ca geothermometers are likely to provide reasonable estimates of the geothermal reservoir temperature.

For a rift in an earlier stage of development, as represented by stage 2, the crustal isotherms may not be sufficiently high to melt the crust and, thus, generate silicic magmatism. In such a case, the main magma type may be basaltic. Such magmas may be generated from a partial melt zone within the mantle and be transported to the surface in a time span involving days or even hours. These magmas may not reside within the crust for a sufficient period of time to impart enough heat to generate significant geothermal systems. The geothermal systems in such rifts, if they exist at all, will not be closely associated with the most recent volcanics; rather, such geothermal systems must originate entirely with the hydrologic cycle, that is, the systems involve deeply circulating groundwater and convective transfer of heat from the recharge to the discharge area. Such geothermal systems are generally low-temperature ($< 100^{\circ}\text{C}$) and will tend to be associated with faults, steeply dipping contacts, or other structural features which permit the vertical ascension of the heated groundwater.

An increasing body of evidence suggests that these geothermal systems may result as a consequence of forced convection at groundwater barriers or constrictions. The geothermal fluids are not generally enriched in volcanic volatiles, and many are sufficiently low in salinity as to qualify as potable water supplies. Application of the SiO_2 and Na-K-Ca geothermometers tends to yield subsurface temperature estimates which are more characteristic of the temperatures encountered along the circulation path, rather than the temperatures which may be encountered within the shallow geothermal reservoir. The deep interiors of the sedimentary basins of the Rio Grande Rift do not appear to be major geothermal exploration targets because temperatures reported from the deep oil wells within the Rio Grande Rift are not significantly above what would be predicted from a typical rift gradient (Harder et al., 1980).

5.2 Geologic Setting

The Rio Grande Rift is a north-south trending thermo-tectonic feature extending from central Colorado in the north through New Mexico and into extreme west Texas and northern Chihuahua, where the rift ceases to be recognizable as a distinct tectonic feature. Late-Quaternary faulting, recently active volcanoes, high heat flow, deep sedimentary basins, and numerous areas exhibiting geothermal manifestations exist throughout the entire extent of the Rio Grande Rift (Seager and Morgan, 1979; Swanberg, 1983; Chapin, 1979). Rifting initiated between 32 and 27 m.y. is continuing today although there have been notable periods of quiescence. In general, the late-Quaternary

volcanics (< 5 m.y.) tend to be basaltic in nature, but a significant exception is the silicic Valles Caldera located in northern New Mexico (see Figure 5-1).

The Valles Caldera is located where the Rio Grande Rift intersects the Jemez Lineament (see Figure 5-1), which is a southwest-northeast feature defined by the alignment of late-Pliocene and Quaternary volcanic centers. There is strong evidence that a shallow magma chamber underlies the western portion of the caldera. Figure 5-1 also shows the rough outline of the Rio Grande Rift and the deeper sedimentary basins within the New Mexico, Chihuahua, and Texas portions of the Rift.

The segmented nature of the rift is evident from Figure 5-1. The northern segment extends from Leadville to Alamosa, Colorado, and is characterized as an axial graben system which tapers and finally pinches out in the north. In the south, the main extensional axis shifts towards the eastern shoulder of the rift (Tweto, 1979). The central segment extends from Alamosa, Colorado, to Socorro, New Mexico, and is characterized as a series of echelon basins separated by complex transverse structures. The southern segment extends from Socorro, New Mexico, to El Paso, Texas, and is characterized by parallel basins with intervening ranges. There is considerable disagreement among workers as to the southern extent of the Rio Grande Rift. For the present discussion, the position of Seager and Morgan (1979), who argue effectively that the deep basins in extreme west Texas and northern Chihuahua, Mexico (see Figure 5-1) should be considered as part of the Rio Grande Rift, has been adopted.

Figure 5-1. Distribution of groundwater barriers and constrictions within the New Mexico portion of the Rio Grande Rift.

5.3 Constriction-Related Geothermal Resources

Harder et al. (1980) and Morgan et al. (1981) have proposed that forced groundwater convection, driven by normal groundwater flow through the deep interconnected basins of the Rio Grande Rift, is the primary source mechanism for the plentiful geothermal areas within the rift. The dynamics of this model are shown schematically in Figure 5-2. Groundwater enters the hydrologic cycle at various recharge areas and flows through the basin under the regional hydraulic gradient. At the discharge area, the groundwater may be forced by a barrier or constriction to flow upwards, thus, introducing a vertical component of convective heat transfer and the subsequent formation of a shallow geothermal system. If forced convection can locally increase geothermal gradients to a sufficiently high level, free convection may be initiated, which has been discussed in detail by Morgan et al. (1981).

Many of the known geothermal areas within the Rio Grande Rift can be attributed to this forced convection model. Figure 5-1 shows the known groundwater barriers and constrictions in the New Mexico portion of the Rio Grande Rift and their associated geothermal resources. The close agreement between known occurrences of groundwater barriers and constrictions and known geothermal systems is clear from the data presented in Figure 5-1. In fact, the agreement is sufficiently good as to suggest that the few areas of nonagreement may be a consequence of inadequate data rather than a failure of the model. Of the 17 known barriers and constrictions shown in Figure 5-1, 14 are associated with geothermal activity, and exceptionally high heat flow has been reported near two others (see Table 5-1). The remaining constriction (San Agustin) has been related to the Hot Springs in the Gila National

Figure 5-2. Qualitative forced convection basin model [after Morgan and Daggett (1981)].

Table 5-1. Geothermal activity associated with groundwater barriers and constrictions in the New Mexico portion of the Rio Grande Rift. The data are compiled from Swanberg (1980).

Name	Description
Anapra	A single warm well (31°C). Geothermal area may be in Mexico.
Derry Warm Spring	Spring temperature is 33°C.
Embudo Constriction	No hydrothermal activity. Measured heat flow of 229 mWm ⁻² reported nearby.
Hueco Tanks	Hot wells with temperatures up to 71°C.
La Bajada Constriction	Numerous springs (17 to 23°C) are roughly 10°C above mean air temperature.
Laguna Pueblo Seeps	Several warm seeps (20 to 30°C) aligned north-south on the west side of the Albuquerque Basin.
Las Alturas	Hot wells with temperatures up to 63°C.
Manby Hot Springs	Several springs with temperatures up to 41°C.
No Agua	No hydrothermal activity. Measured heat flow value of 126 mWm ⁻² .
Ojo Caliente	Shallow wells with temperatures up to 36°C. Several springs and wells with temperatures up to 56°C. Reported heat flow of 141 mWm ⁻² .
Radium Springs	Known geothermal resource area. Spring temperature is 53°C.
San Agustin	Possibly feeds hot springs to the Gila National Forest (Morgan et al., 1981).
San Diego Mountain	Hot wells with temperatures up to 53°C. Reported heat flows up to 650 mWm ⁻² .
Socorro Peak	Known geothermal resource area. Several warm springs and wells with temperatures up to 43°C.
Truth or Consequences	Numerous hot wells and springs with temperatures up to 45°C.

Forest, roughly 50 kilometers to the south (Morgan et al. 1981). Conversely, with the exception of the hot springs associated with the Valles Caldera, all of the hot springs systems in the New Mexico portion of the rift whose surface temperature exceed 40°C are located at areas of discharge of the forced convection systems (see Figure 5-1). This statement is not intended to apply at the lower end of the temperature scale where warm wells and springs with temperatures of 20 to 40°C are numerous (Swanberg, 1980).

The essence of the forced convection concept of geothermal formation is that the system operates entirely within the hydrologic cycle and involves the convective transfer of heat away from the recharge area and into the discharge area. Geothermal areas originating in this manner have many features in common. First, these resource areas are most commonly of the low-temperature variety ($<100^{\circ}\text{C}$). The maximum temperatures within these geothermal systems are controlled by the circulation depth and the regional geothermal gradients. High-temperature geothermal fields of this type are probably not common, although their existence is not precluded. Secondly, these areas need not involve surface manifestation of geothermal activity. Three examples from southern New Mexico are Hueco Tanks, Las Alturas, and San Diego Mountain (see Figure 5-1). All three of these fields have reported temperatures in the 60 to 110°C range at depths less than 300 meters, yet none are manifest at the surface.

Thirdly, the chemistry of the thermal fluids is frequently similar to other groundwaters in the area and is controlled by water-rock reactions along the circulation path. These fluids may be more brackish than nearby nonthermal waters due to their longer circulation path and

exposure to higher temperatures where solubility kinetics are more rapid; however, the fluids generally lack the volcanic volatiles typically found in high-temperature geothermal fields and are never the acid-sulfate type waters characteristic of vapor-dominated geothermal systems. Fourth, the SiO_2 and Na-K-Ca geothermometers are likely to provide erratic and unreliable estimates of subsurface temperatures. This situation does not necessarily imply an inherent problem with the geothermometers; rather, the temperature dependent reactions upon which these geothermometers are based are occurring along the circulation path and not within the geothermal system (see Figure 5-2). It is suggested here that erratic geochemical indications are typical of the long circulation paths involved and may be used as an indicator of forced-convection geothermal systems.

Lastly, the hydrothermal plumbing of such systems is controlled by the local geology, and these geothermal areas may be located in different positions relative to the barrier or constriction. Consider, for example, three geothermal systems shown in Figure 5-1. Radium Springs is formed as water exits the Palomas Basin into the Mesilla Basin. The thermal fluids ascend along a zone of weakness formed by the intersection of a Quaternary fault and a small Tertiary pluton. This areally small geothermal area is located at the constriction. The Las Alturas geothermal area is formed as water exits the Jornada Basin into the Mesilla Basin. The thermal fluids here enter a small limestone horst block and flow south. This areally massive geothermal system is located downstream from the constriction. The Laguna Pueblo Seeps are formed as water flows beneath a confining horizon from the Colorado Plateau to the Rio Grande Rift. As the water hits the alluvial barrier

of the rift, the flow ascends to the surface along the basin- bounding fault. This linear (non)geothermal area is located upstream from the barrier.

5.4 Geothermal Resources of the Valles Caldera

The greatest number of geothermal areas in the Rio Grande Rift result from forced convection at groundwater constrictions and barriers. These areas typically exhibit low-temperature geothermal resources. The single notable exception is the Valles Caldera located in north central New Mexico (see Figure 5-1). The Valles Caldera is a major Quaternary silicic volcanic center and constitutes one of the largest high-temperature geothermal reservoirs in the United States.

Figure 5-3 is a temperature gradient contour map of the caldera based on detailed temperature logs from 70 boreholes published by Goupillaud et al. (1981) and Reiter et al. (1976). The temperature gradients have been calculated by the method of least squares over the depth range of 15 to 76 meters. These gradients have been corrected for topographic effects by standard techniques and contoured using a Hermite cubic interpolation routine (see Figure 5-3). The contouring method has been designed to be a very accurate reflection of the measured surface data. The average error between the contours shown in Figure 5-3 and the temperature gradients actually measured in the boreholes is $6.93^{\circ}\text{C}/\text{km}$ or 2.66 % of the average temperature gradient.

Figure 5-4 shows a temperature gradient profile across the portion of the caldera which contains most of the deep geothermal wells. Figures 5-3 and 5-4 clearly demonstrate the high temperature nature of this geothermal area. The average geothermal gradient of the 70

Figure 5-3. Detailed temperature gradient contour map of the Valles Caldera. The contour interval is 100°C/km.

Figure 5-4. Temperature gradient profile across the Valles Caldera. The section AA' is shown in Figure 3-27.

available boreholes is $260^{\circ}\text{C}/\text{km}$, and the gradient exceeds $500^{\circ}\text{C}/\text{km}$ in several specific locations. The $200^{\circ}\text{C}/\text{km}$ contour covers roughly 150 square kilometers of the western part of the caldera.

Measurements of subsurface temperature have been presented by Rice (1981). Several of the most stable temperature-depth logs are reproduced in Figure 5-5. The maximum temperatures are slightly above 300°C , and a typical reservoir temperature is 275°C . The main geothermal system can be characterized as a liquid-dominated geothermal system which underlies local reservoirs of dry steam (Muffler, 1979).

Figure 5-6 shows the regional trend of the temperature gradients over the Valles Caldera. The data are given in the form of a low-order polynomial representation of the observed temperature gradients constructed in the same manner as Figure 5-3, except that a much larger discrepancy is permitted (required) between the contours and the observed data (i.e., $\pm 58.51^{\circ}\text{C}/\text{km}$ or 22.5 % of the average gradient). The purpose of Figure 5-6 is to demonstrate the close correlation between the regional temperature gradient anomaly and the main ring fracture of the caldera. The tectonic process which is controlling the ring fracture system appears to be controlling the regional thermal anomaly as well. This observation is most easily explained by invoking the presence of a cooling magma chamber beneath the western part of the caldera.

5.5 Conclusions

Rift systems which have not undergone extensive lateral extension and for which crustal melting has not occurred are more likely to be

Figure 5-5. Temperature-depth plots for selected geothermal wells in the Valles Caldera. The data have been taken from Rice (1981).

Figure 5-6. Low-order polynomial fit (trend surface) to temperature gradient data and principal tectonic features of the Valles Caldera.

characterized by low-temperature geothermal resources whose temperature ($<100^{\circ}\text{C}$), fluid chemistry (normal groundwater), and tectonic setting (groundwater discharge areas) all reflect conditions which prevail at various parts of the hydrologic cycle. The Rio Grande Rift is an example of this type of rift, which is not to say that the Rio Grande Rift does not have abundant volcanics.

Recent volcanism in the Rio Grande Rift consists primarily of mantle-derived basalts, which have not had sufficient residence time within the crust to generate significant crustal melting. The geothermal resources within the Rio Grande Rift do not correlate well with these young basalts. Rather, the geothermal resources are low in temperature ($<100^{\circ}\text{C}$) and result from forced hydrothermal convection which discharges at constrictions within or at the end of the major sedimentary basins.

Lower crustal invasion of basaltic material has been suggested by Cook et al. (1979), and widespread Quaternary basalts have been extruded upon the surface (Callendar et al., 1983). However, recent silicic volcanic activity is characteristic only of the Valles Caldera in northern New Mexico, and this type of volcanism is not representative of the rift as a whole. Geothermal resources of the high-temperature variety exist only at the Valles Caldera, which has temperatures in the range of 250 to 300°C .

The remainder of the rift is characterized by low-temperature resources which are more closely related to discharge areas of the hydrologic cycle than to the Quaternary basalt fields. The barrier-constriction model of forced hydrothermal convection appears to adequately explain the distribution of these geothermal resources in the

Rio Grande Rift (see Figure 5-1), as well as for the New Mexico portion of the Basin and Range Province (Morgan et al., 1983).

5.6 References

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6.0 Geochemical Data Representing Thermal and Nonthermal Waters from the Valles Caldera*

6.1 Compiled Data

This Chapter 6 contains a detailed study of the geochemistry from the Valles Caldera area, which is the only known high-temperature (e.g., $> 150^{\circ}\text{C}$) geothermal resource area in New Mexico. The geochemical data were compiled from Goff et al. (1981), Goff et al. (1982), and Summers (1976) and are reported as follows:

Table 3-8. Isotope and chemical geothermometry data for the Valles Caldera.

Figure 3-32. Groundwater chemistry for the Valles Caldera.

Actual temperatures, Na-K-Ca and SiO_2 (quartz) geotemperatures, and oxygen and deuterium isotope data for 55 sites are summarized in Table 6-1. Figure 6-1 shows simplified geology of the Valles Caldera and groundwater chemistry for the 55 sites. The water chemistry data are shown in the form of stiff (chemical) diagrams. Both Table 6-1 and Figure 6-1 are included as part of the geothermal resources of New Mexico scientific map series.

6.2 References

Goff, F.E., Grigsby, C.O., Trujillo, P.E., Counce, D., and Kron, A., 1981, Geology, water chemistry, and geothermal potential of the Jemez Springs area, Canon de San Diego, New Mexico: Journal of Volcanology and Geothermal Research, v. 10, p. 227-244.

* The material contained in Chapter 6 was compiled by Dr. Chandler A. Swanberg, Associate Professor of Physics and Earth Sciences, New Mexico State University.

Table 6-1 Isotope and chemical geothermometry data for the Valles Caldera.

Sample Number	Actual Temperature (°C)	Geotemperature (°C)		Oxygen $\delta^{18}\text{O}$ (‰)	Deuterium δD (‰)	Source Common Name
		Na-K-Ca	SiO ₂ (quartz)			
1	11	33	95	12.20	-84.3	-
2	13	34	53	-10.65	-73.0	-
3	11	18	19	-10.60	-73.5	-
4	14	39	85	-11.80	-81.8	-
5	15	37	96	-10.85	-76.5	-
6	27	57	84	-13.45	-94.7	-
7	30	74	87	-14.30	-103.0	-
8	26	50	92	-	-	-
9	28	43	91	-	-	-
10	23	38	127	-11.40	-77.5	-
11	28	44	126	-10.95	-74.1	-
12	30	37	106	-11.25	-76.0	-
13	26	30	110	-	-	-
14	26	33	105	-11.10	-76.3	-
15	29	40	110	-	-	-
16	30	56	123	-11.95	-83.1	-
17	28	56	124	-11.80	-82.5	-
18	26	55	128	-11.65	-81.0	-
19	19	29	119	-11.00	-76.8	-
20	27	41	132	-	-	-
21	90	**	**	-3.25*	-50.2*	Sulphur Springs
22	11	67	105	-	-	-
23	-	51	96	-13.45*	-97.3*	-
24	8	47	106	-	-	-
25	45	54	115	-12.35	-86.4	Spence Hot Springs
26	31	25	107	-12.60	-88.4	McCauley Hot Springs
27	42	71	124	-12.65	-92.0	San Antonio Hot Springs
28	38	81	135	-12.40*	-86.4*	San Antonio Warm Springs
29	48	226	102	-10.60	-84.9	Soda Dam Spring
30a	72	192	133	-11.35*	-83.1*	Jemez Springs
30b	73	190	124	-11.30*	-84.0*	Jemez Aquifer
31	13	47	112	-11.80	-86.9	-
32	20	32	116	-10.90	-74.5	-
34	11	169	58	-12.50*	-92.7*	-
35	18	0	124	-12.30	-88.0	-
36	11	175	56	-12.35	-84.6	-
37	18	82	99	-12.35	-86.6	-
38	17	56	123	-12.75	-91.1	-
39	15	72	104	-12.40	-85.0	-
40	15	61	97	-11.40	-78.2	-
41	8	72	100	-13.75	-98.2	-
42	12	50	98	-12.65	-90.2	-
43	10	47	121	-13.60	-96.5	-
44	10	35	93	-14.25	-99.1	-

Table 8-1. (Continued).

Sample Number	Actual Temperature (°C)	Geotemperature (°C)		Oxygen $\delta^{18}\text{O}$ (‰)	Deuterium δD (‰)	Source Common Name
		Na-K-Ca	SiO ₂ (quartz)			
45	9	18	67	-	-	-
46	19	43	112	-11.30	-81.2	-
48	11	41	80	-12.60	-88.6	-
49	8	38	85	-12.75	-90.5	-
50	6	47	90	-12.55	-87.6	-
51	9	51	109	-12.25	-85.1	-
52	15	51	115	-11.55	-80.5	-
53	17	51	117	-11.60	-80.1	-
54	18	25	111	-11.00	-76.0	-
60	16	19	67	-12.15	-86.2	-
Steam well	93	286	269	-	-	-
GT2	196	-	145	-8.12	-78.9	-

*Chemical and isotopic analyses are based on different discharge points.

**Geothermometers do not apply to acid-sulphate waters.

Figure 6-1. Groundwater chemistry for the Valles Caldera. The numbers refer to the sample numbers given in Table 6-1.

Goff, R., McCormick, T., Trujillo, P.E., Jr., Counce, D., and Grigsby, C.O., 1982, Geochemical data for 95 thermal and nonthermal waters of the Valles Caldera--southern Jemez Mountains region, New Mexico: Los Alamos National Laboratory, Report LA-9367 - OBES, 51 pp.

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7.0 Evaluation of the Na-K, Na-Li, K-Li, SiO₂ (Quartz), SiO₂ (Chalcedony), and Na-K-Ca Geothermometers*

7.1 Introduction

Three new geothermometers, namely, Na-K, K-Li, and Na-Li (Kharaha, 1981) were tested on thermal and nonthermal waters in New Mexico by computing correlations with the widely-accepted SiO₂ (quartz), SiO₂ (chalcedony), and Na-K-Ca geothermometers. Subsurface temperature estimates based on the new geothermometers were planned for use in the geothermal resources of New Mexico scientific map series (Swanberg, 1983) if the correlations warranted use of these new geochemical exploration tools.

7.2 Geothermometer Equations

The equations for the geothermometers which have been evaluated are taken from Kharaka (1981) and Truesdell (1975) and are summarized as follows:

$$\begin{array}{l} \text{SiO}_2 \text{ (chalcedony):} \\ \text{(ppm)} \end{array} \quad T (^{\circ}\text{C}) = \frac{1,015.1}{4.655 - \log \text{SiO}_2} - 273.15;$$

$$\begin{array}{l} \text{SiO}_2 \text{ (quartz):} \\ \text{(ppm)} \end{array} \quad T (^{\circ}\text{C}) = \frac{1,315}{5.205 - \log \text{SiO}_2} - 273.15;$$

* The principal author of Chapter 7 is Dr. Chandler A. Swanberg, Associate Professor of Physics and Earth Sciences, New Mexico State University.

$$\text{Na-K (White and Ellis): } T (^{\circ}\text{C}) = \frac{855.6}{\log (\text{Na/K}) + 0.8573} - 273.15;$$

(ppm)

$$\text{Na-K (Fournier and Truesdell): } T (^{\circ}\text{C}) = \frac{777}{\log (\text{Na/K}) + 0.70} - 273.15;$$

(ppm)

$$\text{Na-K-Ca: } T (^{\circ}\text{C}) = \frac{1,647}{\log (\text{Na/K}) + \beta \log (\sqrt{\text{Ca/Na}}) + 2.24} - 273.15;$$

(moles/liter)

$\beta = 4/3$ for $\sqrt{\text{Ca/Na}} > 1$ and $T < 100^{\circ}\text{C}$

$\beta = 1/3$ for $\sqrt{\text{Ca/Na}} < 1$ or $T (\beta = 4/3) > 100^{\circ}\text{C}$

$$\text{Na-K-Ca: } T (^{\circ}\text{C}) = \frac{1,647}{\log (\text{Na/K}) + \beta \log (\sqrt{\text{Ca/Na}}) + 2.24} - 273.15;$$

(moles/liter)

$\beta = 4/3$ always

$$\text{Na-K (Kharaka): } T (^{\circ}\text{C}) = \frac{810}{\log (\text{Na/K}) + 0.55} - 273.15;$$

(ppm)

$$\text{K-Li (Kharaka): } T (^{\circ}\text{C}) = \frac{850}{\log (\text{K/Li}) + 0.73} - 273.15;$$

(ppm)

$$\text{Na-Li (Kharaka): } T (^{\circ}\text{C}) = \frac{1,590}{\log (\text{Na/Li}) + 0.657} - 273.15;$$

(ppm)

7.3 Methodology

The new geothermometers were initially calibrated by Kharaha (1981) using thermal and nonthermal waters from differing geographic, geologic, and tectonic settings than are represented in northern New Mexico. As a result, it was not possible to precisely validate the new geothermometers because thermal waters covering the entire thermal range (i.e., 5 to 350^oC) are not available from northern New Mexico. Nonetheless, the new geothermometers were compared to and contrasted with the traditional geothermometers to obtain a measure of the relative reliability of the new geothermometers.

Because all geothermometers require some element or ratio of elements whose solubility is temperature dependent, geotemperatures should correlate positively with in-situ temperature. Furthermore, geotemperatures from differing geothermometers should correlate positively among one another. Also, the regression coefficients i.e., intercept (b), slope (m), correlation coefficient (r) and the actual calculated geotemperature all have physical significance and all must be geologically reasonable. Any violation of these simple conditions indicates that the fundamental assumption of water-rock equilibrium has been violated and the geothermometer in question cannot be applied.

In evaluating the new geothermometers, a data set was selected which represents thermal and nonthermal waters from New Mexico and adjacent areas in Chihuahua, Mexico, Texas, and Colorado. The distribution of these waters is given in Table 7-1. The data set contains both thermal and nonthermal waters from four different tectonic settings representing very diverse geologic settings.

7.4 Discussion of Results

Table 7-2 presents the basic geochemical information and Table 7-3 presents the statistical regression coefficients. Figures 7-1 through 7-5 show plots of geotemperature versus in-situ temperature for the SiO_2 (chalcedony), Na-K-Ca, K-Li, and Na-Li geothermometers, respectively.

7.4.1 SiO_2 (Chalcedony) Geothermometer

The SiO_2 (chalcedony) geothermometer is the most reliable of the geothermometers tested. There are no negative temperature values and no values which exceed 350°C , the maximum temperature likely to be

Table 7-1. Distribution of waters used to evaluate the Na-K, Na-Li, and K-Li geothermometers.

Location	Geology	Number of Samples		
		Thermal	Nonthermal	Total
Basin and Range Province	Alluvium	2	9	11
Gila Area	Volcanics	14	8	22
Rio Grande Rift	Diverse	21	8	29
Midcontinent	Sedimentary	1	10	11

Table 7-2. Summary of geothermometry data. The chemical data have been taken from Swanberg (1980).

Field Number	Name	Actual Temperature (°C)	Geotemperature (°C)								SiO ₂ (quartz)	SiO ₂ (chalcedony)
			Na-K ¹	Na-K ²	Na-K ³	Na-Li	K-Li	Na-K-Ca (B=4/3)	Na-K-Ca			
J1	Allen Spring	26	271	367	276	212	50	3	2.8	51.8	17	
J2	Upper Frisco	37	7	22	-5	84	91	52	51.8	97.4	65	
J3	Lower Frisco	43	125	166	116	186	106	108	148.6	121.9	92	
J4	Lower Frisco	40	127	169	119	186	104	97	97.0	114.3	84	
J5	Lower Frisco	49	117	157	109	187	115	116	147.9	131.9	103	
J6	Well	21	172	229	167	192	77	39	38.9	74.1	41	
J7	Warm Spring	25	186	247	182	166	44	53	53.0	78.4	45	
P3	Lightning Dock	81	147	195	140	201	105	142	168.5	158.2	133	
B1	Cleofas	-	202	269	199	125	-1	51	51.0	98.2	66	
B2	Radium Springs	53	233	313	234	164	22	217	223.4	118.1	88	
B5	Derry Spring	-	136	180	128	167	74	117	156.2	81.2	48	
B6	Derry Spring	-	133	177	126	163	71	118	155.7	82.5	50	
B9	T or C	45	159	211	153	183	76	149	175.6	96.2	64	
B10	T or C	41	164	218	159	186	75	150	178.1	96.2	64	
B11	Warm Spring	41	167	222	162	188	76	151	179.5	96.2	64	
B12	Warm Spring	-	132	175	124	166	75	102	150.2	88.6	56	
B13	Sedillo Spring	34	131	175	124	165	75	59	58.5	72.5	39	
B14	Cook Spring	-	115	154	107	170	94	61	61.3	65.8	32	
B17	Spring	28	107	144	98	155	82	67	67.2	86.2	54	

Table 7-2. (Continued).

Field Number	Name	Actual Temperature (°C)	Geotemperature (°C)								
			Na-K ¹	Na-K ²	Na-K ³	Na-Li	K-Li	Na-K-Ca (B=4/3)	Na-K-Ca	SiO ₂ (quartz)	SiO ₂ (chalcedony)
B18	Spring	21	117	156	108	157	76	73	72.6	84.9	52
B19	Yucca Springs	41	164	218	159	185	74	146	176.8	81.2	48
WT3	Gulf Oil Well	69	218	292	217	175	38	188	209.9	175.0	152
WT6	Hot Springs Resort	44	186	247	182	170	47	108	173.4	94.0	62
Gila2	Faywood Hot Spring	54	177	235	172	193	75	78	78.4	97.2	65
Gila4	Mimbres Hot Spring	58	39	60	28	171	203	75	74.5	106.8	76
Gila5	Gila Hot Spring	63	75	104	65	204	197	76	76.3	119.8	90
Gila6	Gila Hot Spring	66	72	100	62	201	197	77	77.3	120.5	91
Gila7	Hot Spring	65	70	97	59	223	245	74	74.4	128.9	100
Gila8	Hot Spring	44	59	84	48	206	236	62	62.2	128.9	100
LD1	Well	25	108	145	99	160	88	108	141.6	84.0	51
LD2	Well	33	130	173	122	181	95	107	150.6	91.2	59
LD3	LB Well	-	191	254	188	157	32	61	61.3	95.3	63
LD4	Lone Hill Well	-	24	41	12	151	201	58	57.6	82.5	50
LD5	Well	-	71	98	60	161	130	94	94.3	99.1	67
LD6	Well	-	155	206	149	166	60	36	35.8	89.5	57
LD7	Well	24	219	293	218	-	-	-	21.3	99.5	-
LD8	Well	21	134	178	126	159	66	19	18.9	97.2	65
LD9	Well	19	585	902	653	-	-	-	44.7	99.5	-
LD10	Well	-	675	1085	768	-	-	-	57.6	90.0	-

Table 7-2. (Continued).

Field Number	Name	Actual Temperature (°C)	Geotemperature (°C)								SiO ₂ (quartz)	SiO ₂ (chalcedony)
			Na-K ¹	Na-K ²	Na-K ³	Na-Li	K-Li	Na-K-Ca (B=4/3)	Na-K-Ca			
LD11	Well	18	226	302	225	132	-2	70	69.9	104.0	73	
LD12	Well	18	316	434	326	-	-	-	50.3	86.7	-	
LD13	Cienega Springs	17	259	350	263	-	-	-	56.2	90.9	-	
LD14	Well	25	13	28	1	-	-	-	38.2	51.0	-	
LD15	Well	21	269	364	274	-	-	-	38.6	99.5	-	
LD16	Well	19	277	375	282	-	-	-	27.3	93.5	-	
LD17	Well	22	204	272	202	185	53	23	23.3	95.9	64	
LD18	Well	-	57	81	46	190	208	35	35.1	94.8	63	
Gila20	Spring on Turkey Creek	74	74	102	63	161	126	56	56.2	116.5	86	
Gila21	Turkey Creek	28	108	145	99	138	60	54	53.8	101.8	70	
Gila22	Spring on Turkey Creek	70	54	77	43	187	208	68	68.3	117.4	87	
Gila23	Well	29	59	84	49	190	201	51	50.5	66.0	32	
Gila24	Spring	31	50	73	39	154	151	42	41.8	85.3	53	
Gila25	Well	-	52	76	41	170	178	68	67.5	99.5	68	
Gila26	Well	19	46	69	35	197	247	24	24.0	101.2	70	
Gila27	Well	20	1	15	-11	178	365	67	66.7	113.5	83	
Gila29	Mangas Springs	27	294	401	302	-	-	-	49.5	108.7	-	
Gila30	Spring	24	43	65	32	169	194	78	77.8	100.1	68	
R1	Well	25	160	212	154	130	20	74	74.1	120.0	90	
R2	Windmill	23	154	204	148	144	37	61	61.3	114.5	84	

Table 7-2. (Continued).

Field Number	Name	Actual Temperature (°C)	Geotemperature (°C)								
			Na-K ¹	Na-K ²	Na-K ³	Na-Li	K-Li	Na-K-Ca (B=4/3)	Na-K-Ca	SiO ₂ (quartz)	SiO ₂ (chalcedony)
NM1	Montezuma Hot Spring	48	92	125	82	230	184	124	138.2	120.0	90
NM5	Montezuma Hot Spring	32	90	122	80	211	184	136	140.3	121.7	92
NM15	Spring	27	174	231	169	227	113	81	80.5	68.8	35
NM16	Spring	29	177	235	173	229	113	80	79.5	68.8	35
NM18	Spring	25	178	237	174	226	109	80	79.8	66.2	32
NM19	Ojo Caliente	43	99	134	90	245	227	158	157.8	114.5	84
NM22	Ponce de Leon	34	79	109	69	199	181	92	91.6	105.9	75
NM27	Little Arsenic Spring	15	219	293	219	160	24	46	45.7	86.5	54
NM29	Manby Hot Spring	38	148	197	142	221	128	90	89.7	110.1	79
NM30	Manby Hot Spring	33	178	236	173	218	101	73	73.4	110.5	80
NM31	No Name Spring	41	169	225	164	214	103	110	167.7	116.0	86
NM33	Pagosa Hot Spring	57	182	242	178	258	142	158	187.5	111.3	81
NM34	Hot Spring	-	-8	4	-20	-	-	-	21.7	92.2	-
T1	Well	-	437	629	469	175	-14	51	50.8	80.8	48
T2	Well	-	59	84	48	130	96	65	64.7	35.9	1
T3	Well	-	92	125	82	133	67	75	74.9	59.5	25
T4	Windmill	-	41	62	30	106	81	46	46.2	87.7	55
T5	Windmill	-	20	36	8	145	196	-	69.7	37.6	3
T9	Well	-	36	56	25	128	126	-	66.8	94.9	63
T10	Well	-	-5	8	-17	103	157	-	82.0	17.2	-18

Table 7-2. (Continued).

Field Number	Name	Actual Temperature (°C)	Geotemperature (°C)								
			Na-K ¹	Na-K ²	Na-K ³	Na-Li	K-Li	Na-K-Ca (B=4/3)	Na-K-Ca	SiO ₂ (quartz)	SiO ₂ (chalcedony)
T11	Windmill	-	17	34	5	114	134	-	54.9	95.4	63
T12	Well	-	50	73	39	147	139	-	71.6	56.4	22
T13	Windmill	-	56	81	45	141	118	-	137.3	-6.6	-41
T14	-	-	294	402	302	224	51	-	25.8	66.2	32

¹Computed by the White and Ellis formula.

²Computed by the Kharaka formula.

³Computed by the Truesdell formula.

Table 7-3. Regression coefficients for various geothermometers against in-situ spring and well temperatures. Sample size = 51.

Geothermometer	Intercept (b)	Slope (m)	Correlation Coefficient (r)
SiO ₂ (chalcedony) ¹	33	0.99	0.66
SiO ₂ (quartz) ¹	67	0.90	0.66
Na-K (Kharaka) ²	207	-0.87	-0.17
Na-K (Fournier and Truesdell) ¹	141	-0.52	-0.14
Na-K (White and Ellis) ¹	154	-0.61	-0.17
Na-K-Ca ¹	37	1.54	0.47
Na-K-Ca (B = 4/3) ¹	36	1.32	0.50
K-Li (Kharaka) ²	76	1.07	0.24
Na-Li (Kharaka) ²	163	0.55	0.29

Source:

1. Truesdell (1975).
2. Kharaka (1981).

Figure 7-1. SiO_2 (chalcedony) geotemperature vs. in-situ temperature.

Figure 7-2. Na-K-Ca geotemperature vs. in-situ temperature.

Figure 7-3. Na-K-Ca ($\beta = 4/3$) geotemperature vs. in-situ temperature.

Figure 7-4. K-Li geotemperature vs. in-situ temperature.

Figure 7-5. Na-Li geotemperature vs. in-situ temperature.

encountered in a geothermal system (see Table 7-2). The correlation coefficient (r) is both positive and the highest of all the geothermometers. The slope (m) is 0.99 and is essentially equal to the theoretically ideal value of 1.0. The intercept value (b), whose physical significance is the mean temperature at the top of the water table, is 33°C (see Table 7-3 and Figure 7-1). On an absolute scale, this value is easily within 50% of the true temperature, and on a relative scale, the value is the most realistic of all the geothermometers. This geothermometer is used herein as a standard for evaluating the remaining geothermometers.

7.4.2 SiO_2 (Quartz) Geothermometer

The SiO_2 (quartz) geothermometer is based upon the same data as the SiO_2 (chalcedony) geothermometer, and, therefore, the regression coefficients are similar (see Table 7-3). The only difference between the two correlations is a slightly lower slope and a higher intercept for the SiO_2 (quartz) geothermometer, both of which result from a greater degree of quartz disequilibrium at lower temperatures.

7.4.3 Na-K-Ca Geothermometer

Tables 7-2 and 7-3 and Figure 7-2 all indicate that the Na-K-Ca geothermometer provides meaningful estimates of subsurface temperature. The results are even more impressive if the constant is held at $4/3$ (see Figure 7-3). The Na-K-Ca geothermometer, along with the SiO_2 geothermometer, are the only two quantitative geothermometers which have gained widespread acceptance throughout the geothermal industry. These geothermometers are used as a standard in this evaluation of the Kharaka (1981) geothermometers.

7.4.4 Na-K Geothermometer

The geotemperatures calculated using the three Na-K geothermometers (see Table 7-2) and the regression of the geotemperatures against in-situ temperature (see Table 7-3) clearly show that these geotemperatures are not providing realistic estimates of subsurface temperatures. The most obvious problems are the small correlation coefficients, the negative slopes, and the fact that several of the geotemperatures fall outside the range of geologic acceptability (i.e., 20 to 350°C). These geothermometers all fail primarily because the presence of calcium is not accounted for.

7.4.5 K-Li Geothermometer

The K-Li geotemperatures are plotted against in-situ temperature in Figure 7-4 and the regression coefficients are given in Table 7-3. Although the slope and intercept appear reasonable and the geotemperatures fall within the acceptable range, the correlation coefficient is too low to put much confidence in this geothermometer. Furthermore, there appears to be regional bias with both thermal and nonthermal samples from the Gila area yielding geotemperatures almost double the values obtained from samples collected from other locations. Therefore, lacking clear evidence that the ratio of potassium to lithium is being controlled by a temperature dependent chemical reaction, the results obtained using this geothermometer have not been interpreted in regard to the geothermal potential of north central New Mexico.

7.4.6 Na-Li Geothermometer

The Na-Li geothermometer (see Figure 7-5) has not been used in the geothermal evaluation for the same reasons as discussed for the K-Li geothermometer.

7.5 Conclusions

Nine geothermometers (see Table 7-2) have been applied to roughly 2,000 groundwater samples from north central New Mexico and to about 100 additional geothermal waters from New Mexico and adjacent areas in Colorado, Texas, and Chihuahua, Mexico. Although the geothermometers may vary in reliability, the computed geotemperatures may be used to search for samples which are consistently hot according to geotemperature values. There are only two areas which consistently fall more than one standard deviation above the mean on the basis of all the geothermometers and both fall within north central New Mexico. These two areas, Ojo Caliente and Montezuma Hot Springs, are likely to have subsurface temperatures as high as 125°C. Other areas which are more than one standard deviation above the mean on the basis of most (but not all) of the geothermometers include: Pagosa Springs in Colorado; Ojo Del Diablo in Chihuahua; Ojo Caliente in Chihuahua; Lightning Dock in New Mexico; Gila Hot Springs in New Mexico; and the Gulf Oil Well in west Texas. Unfortunately, the Na-K, Na-Li, and K-Li geothermometers of Kharaka (1981) do not appear to be applicable to the low-temperature geothermal resources that are typical of New Mexico. However, all three of these geothermometers provide reasonable subsurface temperature estimates at the Valles Caldera in northern New Mexico, which is the type of high-temperature geothermal resource for which these geothermometers were meant to apply.

7.6 References

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8.0 Temperature Gradient Drilling in North Central New Mexico*

8.1 Introduction

A shallow temperature gradient hole drilling program was conducted in an effort to gain additional information about the possible size and controlling trends of probable geothermal resource areas in north central New Mexico (see Figure 8-1). Twelve shallow temperature gradient holes were drilled in four distinct areas located within the study area. The areas to be drilled were selected on the basis of the results of the geothermal resource assessment of north central New Mexico described in Chapter 1. An attempt was made to sight the holes in each area in the locations that appeared most favorable according to existing geological and geophysical data. This approach was severely restricted by problems with land status and accessibility. Because of constraints on conducting the drilling program on Indian, private, and U.S. Forest Service lands, the shallow temperature gradient holes were sited only on federal lands administered by the Bureau of Land Management (BLM). In addition, due to very limited funds available for the drilling project, the holes had to be sited near existing roads that were in fairly good condition. This situation, coupled with the fact that very few federal lands managed by the BLM are located in choice exploration areas, resulted in the placement of most of the drill holes in less than optimal locations with respect to investigating the thermal anomalies and gaining valuable geological and geophysical data about each area.

*The principal authors of Chapter 8 are Richard L. Lohse, Geothermal Field Engineer, and James T. Gross, Staff Geologist, New Mexico State University Energy Institute.

The four study areas shown in Figure 8-1 that were chosen for the shallow temperature gradient hole drilling program are, from north to south, Ojo Caliente, San Ysidro, Rio Puerco, and Polvadera, New Mexico. The two holes in the Ojo Caliente area, NC-1 and NC-2, were drilled to 150 feet. In the San Ysidro study area, holes NC-3, NC-5, and NC-6 were drilled to 100, 200, and 150 feet, respectively. The hole labeled NC-4 in the San Ysidro area could not be drilled because of problems with land status. Three holes (NC-7, NC-9, and NC-10) were drilled to 150 feet in the Rio Puerco study area, while the hole designated NC-8 could not be drilled because of inaccessibility. Three holes (NC-11, NC-12, and NC-14) were drilled to 200 feet and one hole, NC-13, was drilled to 150 feet in the Polvadera study area.

8.2 Temperature-Depth Data

Temperature measurements were taken at 5-meter intervals in all of the holes and are presented in Appendix A. As an example, the temperature-depth data of drill hole NC-7 are given in Table 8-1 and Figure 8-2. Table 8-1 also gives a generalized lithology of the drill hole and the corresponding estimated thermal conductivities, calculated temperature gradient, estimated heat flow, best estimate heat flow value, and other information such as the location, total depth, and elevation.

The depth intervals for which temperature gradients are calculated are given in Appendix A for all 12 holes and in Table 8-1 for hole NC-7. The representative temperature gradients for each of these intervals were computed using a least-squares fit routine. The standard error of the estimate for each temperature gradient is also reported for each depth interval. Data collected above 15 meters in depth were not used

Table 8-1. Temperature-depth data for hole NC-7.

Location: latitude, 34°44.4', longitude, 107°04.9', township & range, T6N.R2W.SEC18.444; elevation, 1,689 meters; spudded, 8-15-83; temperature logged, 9-10-83; total depth, 45.7 meters; depth of 1½ inch PVC casing, 45.0 meters; bottom-hole temperature, 18.74; bottom-hole depth, 45.0 meters; bottom-hole temperature gradient, 83.1°C/km; best estimate heat flow value, 70 mW/m² (1.7 HFU).

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Lithology	K* (W/m-°K)	Estimated Heat Flow		Remarks
					(mW/m ²)	(HFU)	
5	17.69	46.4 ± 0.8	argillaceous pebble sand	1.4			
10	17.06						
15	17.36						
20	17.56		silty, sandy clay	1.5	69.6	1.67	
25	17.77						
30	18.01						
35	18.25						
40	18.50						
45	18.74						

*Estimated thermal conductivity values.

Figure 8-2. Temperature-depth curve for hole NC-7.

in calculating temperature gradients in order to avoid diurnal and annual temperature disturbances. Bottom-hole temperatures range from 15.6°C at 45 meters in the San Ysidro area to 21.2°C at 60 meters in the Polvadera area. The highest temperature gradient of 92.4°C/km was computed for drill hole NC-1 in the Ojo Caliente area, while the lowest value of 26.8°C was calculated for hole NC-6 in the San Ysidro area.

8.3 Lithologic Data

Nine of the 12 holes drilled, including all of the holes in the Ojo Caliente, Rio Puerco, and Polvadera areas, were completed in late-Tertiary to early-Quaternary Santa Fe Group fan and fluvial deposits. The three holes drilled in the San Ysidro area were completed in Triassic and Cretaceous clastic rocks. A detailed lithology of each of the shallow temperature gradient holes is given in Appendix B. Table 8-2 shows an example (NC-7) of one of these lithologic logs. A generalized lithology for each hole has been produced from the detailed lithologic log for the purpose of estimating thermal conductivities and calculating heat flow values (compare Tables 8-1 and 8-2).

8.3.1 Ojo Caliente Area

Both holes NC-1 and NC-2 were drilled on benches approximately 20 feet above the Rio Ojo Caliente. Hole NC-1 was drilled at the intersection with the tributary Arroyo de los Galves, and hole NC-2 is located where Arroyo Gavilan joins the Rio Ojo Caliente. Both of these tributary drainages contain intermittent streams and neither was flowing at the time of drilling. Surface flow along these arroyos is probably confined to spring run-off and brief summer rainstorms. The Rio Ojo Caliente is a perennial stream.

Table 8-2. Lithologic log for hole NC-7.

Date drilled: August 15, 1983
 Spudded: 9:30 am
 Finish drilling: 12:00 noon
 Total depth: 150 feet
 Hole diameter: 5 inches
 Drilling fluid: 0 to 20 feet, air; 20 to 150 feet, air/foam
 Pipe: 1½ inch PVC, schedule 40

Depth (ft)	Description
0 to 60	Unconsolidated alluvium; probable fluvial origin (Santa Fe Group?); clay, silt, sand, granules, and pebbles. 10% pink to reddish-brown silty, sandy clay; 80% lithic sand, mostly basalt fragments (black, porphyritic) and quartz; 10% gravel-size (granules and pebbles) material. Nearly all gravel is composed of basalt, some fragments of sandstone. Gravel is rounded and subrounded.
60 to 110	50% reddish-brown clay; 40% silt and sand, mostly coarse sand; 10% granules and pebbles.
110 to 120	90% sand: mostly coarse lithic sand; 10% reddish-brown clay.
120 to 150	Same as 60 to 110 ft.

Both holes NC-1 and NC-2 were completed in a poorly consolidated sandy pebble gravel. The depth of burial for these sediments was probably no more than 200 to 250 feet because these sediments are almost certainly related to the aggradation surface that is 70 to 80 feet higher. Compaction and cementation are quite low and overall formation porosity is probably at least 20%. No formation water was produced during air drilling so the thermal conductivity values are based on subsaturated alluvium with approximately 20% porosity.

8.3.2 San Ysidro Area

Hole NC-3 was drilled on a narrow pediment formed on Triassic rocks of the Chinle Formation. The upper 10 feet penetrated Quaternary colluvium and travertine and the lower 90 feet was interbedded clay, siltstone, and sandstone of the Chinle. A color contrast at 50 feet suggests that the zone from 10 to 50 feet is the Petrified Forest Member and that below 50 feet the hole penetrates the Agua Zarca Sandstone Member. This hole was completed at 100 feet to avoid penetrating artesian aquifers that might mask the true formation temperatures.

Both holes NC-5 and NC-6 were completed in the Cretaceous Mancos Shale. Hole NC-6 contained only clay and shale; however, hole NC-5 had a 20 foot thick bed of sandstone from 150 to 170 feet. The porosity of this sandstone probably is near 30% because the samples exhibited little or no cementation and were composed of very well-sorted, well-rounded, fine-grain quartz sand.

8.3.3 Rio Puerco Area

Holes NC-7, NC-9, and NC-10 were drilled into partially consolidated late-Tertiary to early-Quaternary sediments of the Santa Fe Group. The sands, silts, and clays of holes NC-7 and NC-9 were probably

deposited in an old flood plain. The gray to olive clay and silt of hole NC-10 may have been deposited in an old lake.

All three holes were consolidated enough to drill with dry air; foam injection was only needed to lift pebble-size clasts and the larger drill chips of cemented siltstone and sandstone. Overall formation porosity for these holes is probably 15 to 20%. No formation water was produced during air drilling; thus, the water table is deeper than 150 feet in this area. Thermal conductivities are estimated for subsaturated alluvium, although the fine-grain sediments in holes NC-9 and NC-10 may be effectively saturated by vadose water.

8.3.4 Polvadera Area

Holes NC-11 and NC-12 penetrated partially consolidated sand, silt, and clay that are interpreted as fluvial deposits. Although these deposits exhibited some cementation, overall porosity probably is still in the range of 15 to 20%.

Hole NC-13 was very poorly consolidated and penetrated interfingering fan gravels and fluvial sands. Although there was little or no evidence of cementation, formation porosity is probably 15% or less because of very poor sorting of grain sizes.

Hole NC-14 penetrated an unconsolidated fan deposit of mudflow and sheet wash sediments. Grain size in this unit varies from silt to boulders. Some caliche cement is evident in outcrops; however, caliche cement was not observed in the samples. Formation porosity is variable but probably in the range of 15 to 20%. None of the holes in the Polvadera area reached the water table.

8.4 Estimated Thermal Conductivities

Thermal conductivity values were estimated from measured value ranges of similar formations and from observations of sample and outcrop characteristics. Partially consolidated formations were assigned higher thermal conductivities than unconsolidated formations of the same lithology. Estimates of thermal conductivity values ranged from 1.4 to 2.5 W/m-°K and are summarized in Table 8-3.

Recent alluvium with little or no compaction and/or cementation (unconsolidated) was assigned a value of 1.4 W/m-°K. Most of the partially consolidated formations of clay, silt, sand, and gravel were assigned values of 1.5 W/m-°K; more quartz-rich varieties were estimated at 1.6 W/m-°K. The well-sorted, fine-grain quartz sandstone in hole NC-5 was assigned a value of 2.5 W/m-°K. This value is not a high conductivity for a quartz sandstone; however, this unit was poorly cemented and apparently dry. The thermal conductivity of the interbedded sequence of shale and quartz sandstone at the bottom of hole NC-5 was obtained as a weighted average of the thermal conductivities for the shale and the quartz sandstone.

8.5 Estimated Heat Flow

Heat flow values for specified depth intervals were calculated for each of the holes as a product of measured temperature gradients and estimated thermal conductivities. When multiple heat flow values were calculated for a given hole, the best estimate heat flow value for the hole represents a simple average of the heat flow values. The best estimate heat flow values range from 40 mW/m² (1.0 HFU) to 139 mW/m² (3.3 HFU).

Table 8-3. Summary of estimated thermal conductivities for the north central New Mexico study areas.

Area	Lithology	Estimated Thermal Conductivity (W/m-°K)	Remarks
Ojo Caliente	sandy pebble gravel and talus	1.4	unconsolidated
	sandy pebble gravel	1.5	partially consolidated
San Ysidro	sand, silt, clay, and travertine	1.4	unconsolidated
	sand, silt, clay, and shale	1.5	partially consolidated
	interbedded shale and quartz sandstone	1.8	
	very fine-grain sandstone and siltstone	2.1	
	well-sorted, fine-grain quartz sandstone	2.5	poorly cemented
Rio Puerco	argillaceous, silty, pebbly sand	1.4	unconsolidated
	silty, sandy clay	1.5	
	interbedded sandstone, siltstone, and clay	1.5	partially consolidated
Polvadera	silty, sandy gravel	1.4	unconsolidated
	argillaceous, silty, sandy gravel	1.4	unconsolidated
	argillaceous, silty, sandy gravel	1.5	partially consolidated
	sandy gravel	1.5	
	pebble gravel	1.5	
	silty, sandy clay	1.5	
	argillaceous, silty sandstone	1.6	partially consolidated
	interbedded siltstone and sandstone	1.6	partially consolidated

8.6 Discussion

The Ojo Caliente, San Ysidro, Rio Puerco, and Polvadera study areas are shown in Figures 8-3 through 8-6, respectively. Included in these figures are the major highways and roads, population centers, topographic contours, perennial and intermittent streams, tributary arroyos, drill hole names and locations, and selected drill hole information (i.e., bottom-hole temperature and depth data and best estimate heat flow values).

8.6.1 Ojo Caliente Area

The highest calculated temperature gradient and best estimate heat flow values were encountered in the Ojo Caliente study area (see Figure 8-3). The computed temperature gradients range from 65 to 92°C/km and the best estimate heat flow values are 139 and 108 mW/m² (3.3 and 2.6 HFU) for holes NC-1 and NC-2, respectively. The data suggest that the thermal anomaly increases to the north toward the town of Ojo Caliente where surface springs have temperatures measured at 54°C. There are also several warm springs (e.g., temperatures ranging from 22 to 28°C) located approximately 5 miles to the north of the hot springs at Ojo Caliente which, when combined with the drill hole data, strongly suggest a N-S trend to the thermal anomaly, now known to have a longitudinal extent of approximately 10 miles.

8.6.2 San Ysidro Area

The next study area to the south, the San Ysidro study area (see Figure 8-4), had the lowest temperature gradient and best estimate heat flow values of the four study areas. Although hole NC-3 has a computed temperature gradient of 52°C/km and a best estimate heat flow value of 93 mWm⁻² (2.2 HFU), holes NC-5 and NC-6 have calculated temperature gradients as low as 27°C/km and best estimate heat flow values of

OJO CALIENTE STUDY AREA

▲ NC-1 LOCATION AND NAME OF DRILL SITE
 17.5/45/3.3 BOTTOM-HOLE TEMPERATURE (°C) / BOTTOM-HOLE DEPTH (M) / HEAT FLOW (HFU)

Figure 8-3. Location map and thermal data for the Ojo Caliente study area.

SAN YSIDRO STUDY AREA

▲ NC-3 LOCATION AND NAME OF DRILL SITE
 17.3/30/22 BOTTOM-HOLE TEMPERATURE (°C) / BOTTOM-HOLE
 DEPTH (M) / HEAT FLOW (HFU)

Figure 8-4. Location map and thermal data for the San Ysidro study area.

RIO PUERCO STUDY AREA

▲ NC-7 LOCATION AND NAME OF DRILL SITE
 18.7/45/1.7 BOTTOM-HOLE TEMPERATURE (°C) / BOTTOM-HOLE DEPTH (M) / HEAT FLOW (HFU)

Figure 8-5. Location map and thermal data for the Rio Puerco study area.

POLVADERA STUDY AREA

▲ NC-II LOCATION AND NAME OF DRILL SITE
 21.2/60/2.1 BOTTOM-HOLE TEMPERATURE (°C) / BOTTOM-HOLE DEPTH (M) / HEAT FLOW (HFU)

Figure 8-6. Location map and thermal data for the Polvadera study area.

only 59 mWm^{-2} (1.4 HFU) and 40 mWm^{-2} (1.0 HFU), respectively. These values are well below the background heat flow value of 105 mWm^{-2} (2.5 HFU) for this portion of the Rio Grande Rift, which suggests that the thermal anomalies located to the north do not extend to the south into the study area, as well as suggesting that the study area is located within a significant groundwater recharge area.

8.6.3 Rio Puerco Area

Temperature gradient and heat flow values in the Rio Puerco study area (see Figure 8-5) were also below background values representative of this area of the Rio Grande Rift. Computed temperature gradient and best estimate heat flow values range from 36 to 46°C/km and 55 to 70 mWm^{-2} (1.3 to 1.7 HFU), respectively. The temperature-depth data are believed to be affected by lateral groundwater movement associated with recharge to the local aquifer. The temperature gradient and heat flow values increase mainly towards the north and to a lesser extent towards the west; thus, the results of the shallow temperature study show that temperatures increase toward the east boundary fault of the Mesa Carrizo and away from the area most probably affected by groundwater movement. The center of the thermal anomaly appears to be associated with this east side boundary fault, only several miles to the north. Consequently, the thermal data suggest that the drill holes are located to the south and/or to the east of the main thermal anomaly. The thermal fluids are possibly constrained to movement within a confined aquifer located beneath the Mesa Carrizo and flow easterly prior to ascending to the surface via the eastern boundary fault of the mesa.

8.6.4 Polvadera Area

The Polvadera study area is shown in Figure 8-6. Computed temperature gradient and best estimate heat flow values range from 35 to

62°C/km and 53 to 86 mWm⁻² (1.3 to 2.1 HFU), respectively. Temperature gradient and heat flow values for holes NC-11 and NC-12 are identical, while the corresponding values for hole NC-13 are slightly elevated when considering only the data from the more representative bottom one-half of the hole. The values obtained for these three holes are near regional background values. Hole NC-14, on the other hand, has a computed temperature gradient of only 35°C/km and an abnormally low best estimate heat flow value of 53 mWm⁻² (1.3 HFU). Because hole NC-14 is located further out into the basin where permeabilities are greater and because of the non-linearity of the temperature-depth data in the upper portion of the hole, the temperature data are probably affected by local groundwater flow associated with the Rio Grande and/or its tributary arroyos. The results show that temperatures increase towards the up-lifted Precambrian bedrock to the west and away from the deeper, more permeable interior parts of the basin where groundwater flow can have a significant influence on the temperature data. Comparison of the 15- to 20-meter temperature data, which are measured below the depth of penetration and influence of the diurnal and annual temperature waves, from the shallow temperature gradient holes located in all four study areas shows that this portion of the crust in the Polvadera area is at least several degrees Celsius warmer than that in the other three areas.

Appendix A

Temperature Data for North Central New Mexico

Note: The data are for temperature gradient holes NC-1 through NC-14 (see Figures 8-3 through 8-6 for locations). Holes NC-4 and NC-8 were sited but not drilled. The reported temperature gradient data are least-squares fits to the empirical data, with the standard error of the estimate given. Bottom-hole temperature gradients were computed for a 15°C surface temperature.

Hole Name: NC-1

Location: latitude, 36°16.9', longitude, 106°03.1', township & range, T24N.R8E.SEC25.314; elevation, 1,887 meters; spudded, 8-16-83; temperature logged, 9-5-83; total depth, 45.7 meters; depth of 1½ inch PVC casing, 44.8 meters; bottom-hole temperature, 18.35°C; bottom-hole depth, 44.8 meters; bottom-hole temperature gradient, 74.8°C/km; best estimate heat flow value, 139 mW/m² (3.3 HFU).

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Lithology	K* (W/m-°K)	Estimated Heat Flow		Remarks
					(mW/m ²)	(HFU)	
1	24.14	92.4 ± 1.2	sandy pebble gravel	1.5			
2	23.44						
3	22.24						
4	16.59						
5	15.67						
10	15.20						
15	15.71						
20	16.07						
25	16.52						
30	16.94						
35	17.42						
40	17.92						
44.8	18.35						

*Estimated thermal conductivity values.

Hole Name: NC-2

Location: latitude, 36°15.5', longitude, 106°03.1', township & range, T23N.R8E.SEC1.132; elevation, 1,868 meters; spudded, 8-16-83; temperature logged, 9-5-83; total depth, 45.7 meters; depth of 1½ inch PVC casing, 45.7 meters; bottom-hole temperature, 17.46°C; bottom-hole depth, 45.0 meters; bottom-hole temperature gradient, 54.7°C/km; best estimate heat flow value, 108 mW/m² (2.6 HFU).

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Lithology	K* (W/m-°K)	Estimated Heat Flow		Remarks
					(mW/m ²)	(HFU)	
1	24.91		sandy pebble gravel and gravel talus	1.4			
2	23.78						
3	22.66						
4	21.58						
5	20.52						
10	14.68						
15	15.21	64.6 ± 1.6	sandy pebble gravel	1.5	96.9	2.32	
20	15.56						
25	15.85						
30	16.19	80.0 ± 1.2			120.0	2.87	
35	16.66						
40	17.07						
45	17.46						
45.7	17.51						

*Estimated thermal conductivity values.

Hole Name: NC-3

Location: latitude, 35°32.5', longitude, 106°50.3', township & range, T15N.R1E.SEC9.413; elevation, 1,686 meters; spudded, 8-17-83; temperature logged, 9-5-83; total depth, 30.5 meters; depth of 1½ inch PVC casing, 30.4 meters; bottom-hole temperature, 17.30°C; bottom-hole depth, 30.0 meters; bottom-hole temperature gradient, 76.7°C/km; best estimate heat flow value 93 mW/m² (2.2 HFU).

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Lithology	K* (W/m-°K)	Estimated Heat Flow		Remarks
					(mW/m ²)	(HFU)	
1	25.84		sand, silt, clay, travertine	1.4			
2	24.96						
3	24.35						
4	16.03						
5	15.99						
10	16.20	51.6 ± 3.2	sandy, silty clay; minor siltstone	1.5			
15	16.53						
20	16.73	51.6 ± 3.2	very fine-grain sandstone and siltstone	2.1	108.4	2.59	
25	17.00						
30	17.30	51.6 ± 3.2	sandy clay	1.5	77.4	1.85	
30.4	17.31						

*Estimated thermal conductivity values.

Hole Name: NC-5

Location: latitude, 35°30.1', longitude, 106°49.9', township & range, T15N.R1E.SEC28.244; elevation, 1,759 meters; spudded, 8-17-83; temperature logged, 9-5-83; total depth, 61.0 meters; depth of 1½ inch PVC casing, 61.0 meters; bottom-hole temperature, 17.77°C; bottom-hole depth, 60.0 meters; bottom-hole temperature gradient, 46.2°C/km; best estimate heat flow value, 59 mW/m² (1.4 HFU).

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Lithology	K* (W/m-°K)	Estimated Heat Flow		Remarks
					(mW/m ²)	(HFU)	
1	22.57		clay, silt, and fine sand	1.4			sandstone is well- sorted and fine grain
2	21.09						
3	19.75						
4	18.42						
5	17.41						
10	17.03		silty clay and shale	1.5			
15	16.91						
20	16.88						
25	16.56						
30	16.70						
35	16.87	40.0 ± 2.9			60	1.44	
40	17.10						
45	17.36						
50	17.51	27.2 ± 0.7	quartz sandstone	2.5	68	1.63	
55	17.64		interbedded shale and sandstone as above		49	1.17	
60	17.77						
61	17.80			1.8			

*Estimated thermal conductivity values.

Hole Name: NC-6

Location: latitude, 35°30.2', longitude, 106°51.0', township & range, T15N.R1E.SEC29.244; elevation, 1,750 meters; spudded, 8-17-83; temperature logged, 9-5-83; total depth, 45.7 meters; depth of 1½ inch PVC casing, 45.1 meters; bottom-hole temperature, 15.60°C; bottom-hole depth, 45.0 meters; bottom-hole temperature gradient, 13.3°C/km; best estimate heat flow value, 40 mW/m² (1.0 HFU).

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Lithology	K* (W/m-°K)	Estimated Heat Flow		Remarks
					(mW/m ²)	(HFU)	
1	25.13		silty clay	1.4			
5	21.50						
10	18.79						
15	14.74						
20	14.81						
25	14.95	26.8 ± 3.8	silty clay and silty shale	1.5	40.2	0.96	
30	15.14						
35	15.33						
40	15.48	27.0 ± 1.7			40.5	0.97	
45	15.60						
45.1	15.61						

*Estimated thermal conductivity values.

Hole Name: NC-7

Location: latitude, 34°44.4', longitude, 107°04.9', township & range, T6N.R2W.SEC18.444; elevation, 1,689 meters; spudded, 8-15-83; temperature logged, 9-10-83; total depth, 45.7 meters; depth of 1½ inch PVC casing, 45.0 meters; bottom-hole temperature, 18.74; bottom-hole depth, 45.0 meters; bottom-hole temperature gradient, 83.1°C/km; best estimate heat flow value, 70 mW/m² (1.7 HFU).

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Lithology	K* (W/m-°K)	Estimated Heat Flow		Remarks
					(mW/m ²)	(HFU)	
5	17.69	46.4 ± 0.8	argillaceous pebble sand	1.4			
10	17.06						
15	17.36						
20	17.56						
25	17.77		silty, sandy clay	1.5	69.6	1.67	
30	18.01						
35	18.25						
40	18.50						
45	18.74						

*Estimated thermal conductivity values.

Hole Name: NC-9

Location: latitude, 34°43.7', longitude, 107°04.0', township & range, T6N.R2W.SEC20.414; elevation, 1,682 meters; spudded, 8-15-83; temperature logged, 9-10-83; total depth, 45.7 meters; depth of 1½ inch PVC casing, 44.8 meters; bottom-hole temperature, 17.64°C; bottom-hole depth, 44.8 meters; bottom-hole temperature gradient, 58.9°C/km; best estimate heat flow value, 55 mW/m² (1.3 HFU).

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Lithology	K* (W/m-°K)	Estimated Heat Flow		Remarks
					(mW/m ²)	(HFU)	
1	24.49		argillaceous silt and fine sand	1.4			
2	21.71						
3	19.64						
4	18.09						
5	16.94						
10	16.14						
15	16.54	36.5 ± 0.4	silty, sandy clay	1.5	54.8	1.31	
20	16.75						
25	16.92						
30	17.09						
35	17.27						
40	17.47						
44.8	17.64						

*Estimated thermal conductivity values.

Hole Name: NC-10

Location: latitude, 34°42.7', longitude, 107°04.8', township & range, T6N.R2W.SEC30.444; elevation, 1,734 meters; spudded, 8-15-83; temperature logged, 9-10-83; total depth, 45.7 meters; depth of 1½ inch PVC casing, 45.0 meters; bottom-hole temperature, 17.49°C; bottom-hole depth, 45.0 meters; bottom-hole temperature gradient, 55.3°C/km; best estimate heat flow value, 64 mW/m² (1.5 HFU).

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Lithology	K* (W/m-°K)	Estimated Heat Flow		Remarks
					(mW/m ²)	(HFU)	
1	23.77		silty clay	1.4			
2	21.02						
3	18.81						
4	17.46						
5	16.40						
10	15.82	42.8 ± 0.5	interbedded siltstone, silty clay, and clay	1.5	64.2	1.54	
15	16.19						
20	16.44						
25	16.64						
30	16.84						
35	17.05						
40	17.28						
45	17.49						

*Estimated thermal conductivity values.

Hole Name: NC-11

Location: latitude, 34°13.4', longitude, 106°58.3', township & range, T1S.R1W.SEC17.312; elevation, 1,551 meters; spudded, 8-20-83; temperature logged, 9-6-83; total depth, 62.5 meters; depth of 1½ inch PVC casing, 61.5 meters; bottom-hole temperature, 21.19°C; bottom-hole depth, 60.0 meters; bottom-hole temperature gradient, 103.2°C/km; best estimate heat flow value, 86 mW/m² (2.1 HFU).

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Lithology	K* (W/m-°K)	Estimated Heat Flow		Remarks
					(mW/m ²)	(HFU)	
1	26.12		silty, sandy gravel	1.4			
2	23.08						
3	20.25						
4	18.75						
5	18.15						
10	18.47	53.5 ± 0.8	argillaceous, silty sandstone	1.6	85.6	2.05	
15	18.84						
20	19.06						
25	19.29						
30	19.61						
35	19.82						
40	20.10						
45	20.38						
50	20.71						
55	20.96						
60	21.19						
61.5	21.25						

*Estimated thermal conductivity values.

Hole Name: NC-12

Location: latitude, 34°13.0', longitude, 106°57.9', township & range, T1S.R1W.SEC17.433; elevation, 1,551 meters; spudded, 8-20-83; temperature logged, 9-6-83; total depth, 64.0 meters; depth of 1½ inch PVC casing, 62.2 meters; bottom-hole temperature, 21.00°C; bottom-hole depth, 60.0 meters; bottom-hole temperature gradient, 100.0°C/km; best estimate heat flow value, 86 mW/m² (2.1 HFU).

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Lithology	K* (W/m-°K)	Estimated Heat Flow		Remarks
					(mW/m ²)	(HFU)	
1	25.58	53.6 ± 0.8	interbedded siltstone and sandstone	1.6	85.8	2.05	
2	23.15						
3	21.19						
4	19.59						
5	18.62						
10	18.21						
15	18.66						
20	18.90						
25	19.15						
30	19.42						
35	19.76						
40	19.96						
45	20.28						
50	20.54						
55	20.82						
60	21.00						
62.2	21.17						

*Estimated thermal conductivity values.

Hole Name: NC-13

Location: latitude, 34°14.5', longitude, 106°59.1', township & range, T1S.R1W.SEC7.123; elevation, 1,564 meters; spudded, 8-21-83; temperature logged, 9-6-83; total depth, 45.7 meters; depth of 1½ inch PVC casing, 45.0 meters; bottom-hole temperature, 20.66°C; bottom-hole depth, 45.0 meters; bottom-hole temperature gradient, 125.8°C/km; best estimate heat flow value, 86 mWm² (2.1 HFU).

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Lithology	K* (W/m-°K)	Estimated Heat Flow		Remarks
					(mW/m ²)	(HFU)	
1	25.72		silty, sandy gravel	1.4			argillaceous, silty, sandy gravel
2	22.46						
3	20.40						
4	19.34		(see remarks) pebble gravel				
5	18.80						
10	18.65	52.0 ± 1.2	argillaceous, silty, sandy gravel	1.5	78.0	1.87	
15	18.90						
20	19.15						
25	19.42	62.0 ± 0.4	silty, sandy clay		93.0	2.22	
30	19.72						
35	20.03						
40	20.34						
45	20.66						

*Estimated thermal conductivity values.

Hole Name: NC-14

Location: latitude, 34°13.4', longitude, 106°56.5', township & range, T1S.R1W.SEC16.421; elevation, 1,503 meters; spudded, 8-19-83; temperature logged, 9-6-83; total depth, 64.0 meters; depth of 1½ inch PVC casing, 61.8 meters; bottom-hole temperature, 20.20°C; bottom-hole depth, 60.0 meters; bottom-hole temperature gradient, 86.7°C/km; best estimate heat flow value, 53 mW/m² (1.3 HFU).

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)	Lithology	K* (W/m-°K)	Estimated Heat Flow		Remarks	
					(mW/m ²)	(HFU)		
1	26.80		sandy gravel	1.5				
2	23.32							
3	21.02							
4	19.48							
5	18.59							
10	18.72							
15	18.92							
20	18.93							
25	19.01							
30	19.16							
35	19.28	35.3 ± 1.1				53.0		1.27
40	19.47							
45	19.64							
50	19.87							
55	19.99							
60	20.20							
61.8	20.27							

*Estimated thermal conductivity values.

NC-1

NC-2

NC-3

NC-5

NC-6

NC-7

NC-9

NC-10

NC-11

NC-12

NC-13

NC-14

Appendix B

Lithologic Data for North Central New Mexico

Note: The data are for temperature gradient holes NC-1 through NC-14 (see Figures 8-3 through 8-6 for locations). Holes NC-4 and NC-8 were sited but not drilled.

Hole Name: NC-1

Date drilled: August 16, 1983

Spudded: 2:00 pm

Finish drilling: 3:00 pm

Total depth: 150 feet

Hole diameter: 5 inches

Drilling fluid: 0 to 150 feet, air/foam

Pipe: 1½ inch PVC, schedule 40

Depth (ft)	Description
0 to 150	Sandy pebble gravel; poorly to partially consolidated; minor cementation evident in nearby outcrops. Sand is mostly fine to coarse quartz and rock fragments. Coarse sand and larger material is composed of volcanic detritus, silicic (rhyolite) to intermediate in composition. 30% sand : 70% granules and pebbles. Coarsest interval at 20 to 70 ft with clasts up to 6 mm. Clasts are angular to rounded. Formation is probably a fluvial facies of the Santa Fe Group. The 70 to 150 ft interval is mostly coarse sand and granule size.

Hole Name: NC-2

Date drilled: August 16, 1983
Spudded: 4:15 pm
Finish drilling: 9:00 pm
Total depth: 158 feet
Hole diameter: 5 inches
Drilling fluid: 0 to 155 feet, air/foam
Pipe: 1½ inch PVC, schedule 40

Depth (ft)	Description
0 to 30	Mixed talus and gravel: Talus is composed of small to medium pebble size debris of metamorphic clasts shed from a coarse (pebble to boulder size) stream gravel that is perched on the top of an adjacent ridge. Gravel material probably intertongues with talus since drilling through the first 30 ft was intermittently smooth and rough.
30 to 150	Sandy pebble gravel as at NC-1. Appears to be the same formation that can be traced from NC-1 to NC-2 along Hwy. 285. The 30 to 60 ft interval is mostly coarse sand and granule size. The 60 to 150 ft interval is mostly small and medium pebble size.

Hole Name: NC-3

Date drilled: August 17, 1983
Spudded: 1:25 pm
Finish drilling: 2:30 pm
Total depth: 100 feet
Hole diameter: 5 inches
Drilling fluid: 0 to 100 feet, air/foam
Pipe: 1½ inch PVC, schedule 40

Depth (ft)	Description
0 to 10	Grayish orange and dark yellowish orange sandy travertine and silty, sandy clay.
10 to 20	Pale reddish brown sandy clay. Clay, 60 to 70%. Quartz sand, 30 to 40%.
20 to 30	Pale red silty clay. Clay, 90 to 95%.
30 to 40	Light gray and medium light gray silty clay. Clay, 95%.
40 to 50	Grayish red shale and minor light gray siltstone.
50 to 80	Very light gray and light gray very fine grain sandstone and siltstone.
80 to 90	Light gray sandy clay and subordinate (10%) fine grain quartz sandstone.
90 to 100	No sample taken.

Comments: Surface has been mapped by Woodward, L.A., and Ruetschilling, R.L., 1974, as Quaternary-Tertiary travertine overlying the Petrified Forest Member of the Chinle Formation. Map description of member: reddish-orange and brownish-maroon shale with subordinate reddish sandstone and minor green shale, brown clastic limestone, and small pebble conglomerate; thickness about 1,000 ft.

Hole Name: NC-5

Date drilled: August 17, 1983

Spudded: 4:30 pm

Finish drilling: 6:45 pm

Total depth: 200 feet

Hole diameter: 5 inches

Drilling fluid: 0 to 30 feet, air; 30 to 200 feet, air/foam

Pipe: 1½ inch PVC, schedule 40

Depth (ft)	Description
0 to 10	Unconsolidated pinkish gray clay, silt, and fine sand.
10 to 30	Light gray and medium light gray silty clay and shale.
30 to 150	Medium dark gray to dark gray silty clay and shale. Darker color is due to wet samples.
150 to 170	Very light gray fine grain quartz arenite. Very well sorted, rounded to well rounded clasts. Little or no clay matrix; partially cemented, but probably friable.
170 to 200	50% shale: 50% sand as at the 150 to 170 ft interval. Probably interbedded shale and fine grain sandstone. Increasing clay and shale content towards 200 ft.

Comments: Formation is probably Mancos Shale.

Hole Name: NC-6

Date drilled: August 17, 1983
Spudded: 8:15 pm
Finish drilling: 9:30 pm
Total depth: 150 feet
Hole diameter: 5 inches
Drilling fluid: 0 to 150 feet, air/foam
Pipe: 1½ inch PVC, schedule 40

Depth (ft)	Description
0 to 50	Light olive gray to olive gray silty clay. Recent alluvium along the Canada de las Milpas stream course. Clay content, 95%.
50 to 90	Olive gray and dark gray clay, silty clay, and shale. Most of sample lacks shale character and is wet sticky clay. Mancos Shale.
90 to 110	Dark gray, fissile, silty shale.
110 to 120	Dark gray silty clay.
120 to 150	Medium gray, fissile, silty shale.

Comments: Possible conductivity contrast between clay (higher K) and shale (lower K). No water flow likely through this interval. Drilled on the east flank of a north-northwesterly syncline. Formation from 50 to 150 ft is Mancos Shale.

Hole Name: NC-7

Date drilled: August 15, 1983

Spudded: 9:30 am

Finish drilling: 12:00 noon

Total depth: 150 feet

Hole diameter: 5 inches

Drilling fluid: 0 to 20 feet, air; 20 to 150 feet, air/foam

Pipe: 1½ inch PVC, schedule 40

Depth (ft)	Description
0 to 60	Unconsolidated alluvium; probable fluvial origin (Santa Fe Group?); clay, silt, sand, granules, and pebbles. 10% pink to reddish-brown silty, sandy clay; 80% lithic sand, mostly basalt fragments (black, porphyritic) and quartz; 10% gravel-size (granules and pebbles) material. Nearly all gravel is composed of basalt, some fragments of sandstone. Gravel is rounded and subrounded.
60 to 110	50% reddish-brown clay; 40% silt and sand, mostly coarse sand; 10% granules and pebbles.
110 to 120	90% sand: mostly coarse lithic sand; 10% reddish-brown clay.
120 to 150	Same as 60 to 110 ft.

Hole Name: NC-9

Date drilled: August 15, 1983

Spudded: 2:00 pm

Finish drilling: 4:30 pm

Total depth: 150 feet

Hole diameter: 5 inches

Drilling fluid: 0 to 70 feet, air; 70 to 150 feet, air/foam

Pipe: 1½ inch PVC, schedule 40

Depth (ft)	Description
0 to 70	90% silt and fine sand; minor amounts of reddish-brown clay (~ 10%) as lenses and matrix. Sand is mostly quartz as subangular to rounded grains.
70 to 150	Samples below 70 ft are wet because of foam drilling and because sampler washed them. Some clay, silt, and fine sand is removed in washing. Increasing clay content below 70 ft. Samples from the 80 to 150 ft interval are 50% clay and 50% silt and fine sand.

Hole Name: NC-10

Date drilled: August 15, 1983
Spudded: 5:40 pm
Finish drilling: 6:30 pm
Total depth: 150 feet
Hole diameter: 5 inches
Drilling fluid: 0 to 150 feet, air/foam
Pipe: 1½ inch PVC, schedule 40

Depth (ft)	Description
0 to 15	Light brown silty clay.
15 to 90	Interbedded siltstone, silty clay, and clay. Very light gray, yellowish gray, pale olive. Some beds as coarse as fine sand. Poorly to moderately indurated and cemented silt and sand units.
90 to 110	Light to moderate brown silty, sandy clay. Clay content at least 75%.
110 to 150	Very light gray, yellowish gray, clay, siltstone, and fine grain sandstone. 75% clay at 110 ft decreasing to 10% clay at 150 ft.

Hole Name: NC-11

Date drilled: August 20, 1983
Spudded: 7:00 am
Finish drilling: 11:00 am
Total depth: 203 feet
Hole diameter: 5 inches
Drilling fluid: 0 to 203 feet, mud
Pipe: 1½ inch PVC, schedule 40

Depth (ft)	Description
0 to 10	Poorly sorted mixture of silt, sand, and granule to medium pebble size lithic fragments, mostly volcanics. Minor caliche. Recent stream alluvium.
10 to 205	Mostly fine sand, silt, and clay. Minor pebbles of various origin. Pale brown when wet and pale yellowish brown when dry. Clay content variable, but probably 10 to 20%. Silt and fine sand 70 to 90%. Formation is probably a fluvial facies of the Santa Fe Group. Partially compacted. Bulk formation porosity is still probably at least 20%.

Hole Name: NC-12

Date drilled: August 20, 1983
Spudded: 1:00 pm
Finish drilling: 3:00 pm
Total depth: 213 feet
Hole diameter: 5 inches
Drilling fluid: 0 to 213 feet, air/foam
Pipe: 1½ inch PVC, schedule 40

Depth (ft)	Description
0 to 210	Pale red and pale yellowish brown siltstone and sandstone. Sand size clasts are mostly fine and very fine grain. Clay content probably 10% or less of interval penetrated, both as matrix and thin laminae. Minor (< 5%) pebble content. Formation is partially to well consolidated and probably is an old flood plain deposit.

Hole Name: NC-13

Date drilled: August 21, 1983
Spudded: 7:00 am
Finish drilling: 9:00 am
Total depth: 150 feet
Hole diameter: 5 inches
Drilling fluid: 0 to 150 feet, mud
Pipe: 1½ inch PVC, schedule 40

Depth (ft)	Description
0 to 20	Recent alluvium. Silt, sand, and gravel. Poorly consolidated. 20% silt and sand, 80% gravel. Gravel is composed mostly of silicic to intermediate composition volcanics.
20 to 30	Clay, silt, sand, and gravel. Same as at 0 to 20 ft with the addition of clay.
30 to 50	Pebble gravel. Small and medium pebbles of rhyolite and other volcanics. Very poorly consolidated.
50 to 100	Same as at 20 to 30 ft. Clay, silt, sand, and gravel. Clay content variable 10 to 20%.
100 to 150	Moderate brown, silty, sandy clay. Probably as interbedded silt, sand, and clay. Minor pebble content.

Hole Name: NC-14

Date drilled: August 19, 1983

Spudded: 11:30 am

Finish drilling: 6:30 pm

Total depth: 210 feet

Hole diameter: 5 inches

Drilling fluid: 0 to 210 feet, mud

Pipe: 1½ inch PVC, schedule 40

Depth (ft)	Description
0 to 210	Alluvial fan deposits. Interbedded sheetwash and mudflow deposits consisting of silt to large pebbles. A few cobbles and boulders are visible in nearby outcrop of same formation. Sand and gravel content variable, but overall sand comprises about 25% of formation; gravel approximately 75%.