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**STATE-COUPLED LOW TEMPERATURE GEOTHERMAL
RESOURCE ASSESSMENT PROGRAM, FISCAL YEAR 1982**

Final Technical Report

**By
Larry Icerman**

August 1983

Work Performed Under Contract No. AS07-78ID01717

**New Mexico State University Energy Institute
Las Cruces, New Mexico**

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STATE-COUPLED LOW TEMPERATURE GEOTHERMAL
RESOURCE ASSESSMENT PROGRAM,
FISCAL YEAR 1982

FINAL TECHNICAL REPORT

Edited by

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Principal Investigator

August 1983

 

FOREWORD

This report summarizes the results of low-temperature geothermal energy resource assessment efforts in New Mexico during the period from June 15, 1981 through September 30, 1983, under the sponsorship of the U.S. Department of Energy (Contract DE-AS07-78ID01717). The research program was administered by the New Mexico State University Energy Institute and the research included in this report was conducted by staff members of the United States Geological Survey and the Los Alamos National Laboratory and by university faculty and staff members at New Mexico State University.

The report is divided into four chapters which correspond to the tasks delineated in the above contract. Chapter 5 is a brief summary of the tasks performed under this contract during the period October 1, 1978, through June 30, 1983. This work extends the knowledge of low-temperature geothermal reservoirs with the potential for direct heating applications in New Mexico. The research effort focused on compiling basic geothermal data throughout selected areas in New Mexico in a format suitable for direct transfer to the U.S. Geological Survey for inclusion in the GEOTHERM data file and to the National Oceanic and Atmospheric Administration for use with New Mexico geothermal resources maps. Funding from the New Mexico Energy Research and Development Institute (Contract NMERDI 2-69-2208) supported work from which much of the data compiled in Chapter 4 were taken.

We acknowledge the special efforts of Diane Prince, who typed the draft versions of the completed manuscript.

L. Icerman

A. Starkey

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Chapter 1

Scientific Geothermal Resources Map Series for New Mexico*

Introduction

The purpose of this task was to compile all geothermally related scientific data for the state of New Mexico and present these data in a series of maps designed for use by the scientific community to be published by the National Geophysical and Solar-Terrestrial Data Center of the National Oceanic and Atmospheric Administration (NOAA) in 1983. All appropriate data have been collected and forwarded to NOAA for the preparation of the final map series.

Status of Each Map in the Series

The status of each specific map to appear in Geothermal Resources of New Mexico: Scientific Map Series (Swanberg, 1983) and the data sets included therein follow. (See Selected Technical References and Additional References at the end of this chapter for published material used in the compilation of the maps.)

Map 1. Late Tertiary and Quaternary Tectonics and Volcanism was completed in 1982 by J.F. Callender, W.R. Seager, and C.A. Swanberg. It includes the following data sets and credits:

1. Late Tertiary and Quaternary faults compiled by J. F. Callender for northern New Mexico and W.R. Seager for southern New Mexico utilizing published and unpublished material.

* The principal author of Chapter 1 is Dr. Chandler A. Swanberg, Associate Professor of Physics and Earth Sciences, New Mexico State University.

2. Late Tertiary and Quaternary volcanics compiled by J.F. Callender for northern New Mexico and W.R. Seager for southern New Mexico utilizing published and unpublished material.
3. Late Tertiary and Quaternary volcanic centers compiled by J.F. Callender for northern New Mexico and W.R. Seager for southern New Mexico utilizing published and unpublished material.
4. Late Tertiary and Quaternary age dates compiled by A. Kudo, W. E. Elston, and J.F. Callender utilizing published and unpublished material. Additional unpublished age dates were provided by A.W. Laughlin, W.R. Seager, and W.S. Baldrige.
5. Heat flow compiled by C.A. Swanberg utilizing published material.
6. Thermal wells and springs compiled by C.A. Swanberg utilizing published and unpublished material.
7. Regions of high geothermal potential interpreted by C.A. Swanberg.
8. Fundamental geographic data provided by NOAA.
9. Valles Caldera inset: major structural features and a trend surface representation of the temperature gradient data compiled by Swanberg (1982).
10. Valles Caldera inset: deep geothermal wells and contour map representation of temperature gradient data compiled by C.A. Swanberg (1982).
11. Valles Caldera inset: detailed temperature logs from selected geothermal wells as interpreted by C.A. Swanberg on the basis of the data of Rice (1981).
12. Seismic epicentral inset: data taken from Sanford (1980, 1982).
13. Anomalously hot oil and gas wells inset: data taken from Chaturvedi (1982).
14. Heat flow contour map inset: data taken from Seager and Morgan (1979) and Swanberg (1979).
15. Seismic risk inset: data taken from Algermissen and Perkins (1976).

Map 2. Hydrology and Geochemistry was completed in draft form in 1983 by J.F. Callender, V. Harder, P. Morgan, and C.A. Swanberg and is being prepared for production. It includes the following data sets and credits:

1. Deep sedimentary basins compiled by J.F. Callender on the basis of published and unpublished material and supplemented by unpublished material provided by F. Birch.
2. Groundwater barriers and constructions as interpreted by V. Harder and P. Morgan.
3. Detailed temperature gradient contours within the San Juan and Permian Basins as interpreted by P. Morgan and C. A. Swanberg. These contours are based on temperatures measured during the logging of deep oil and gas wells.
4. Locations of additional oil and gas wells where temperature data are too sparse to permit reliable contouring.
5. Stiff diagrams depicting major element geochemistry for thermal waters of New Mexico compiled and interpreted by C.A. Swanberg.
6. Estimated subsurface temperatures as calculated from the silica and Na-K-Ca geothermometers for geothermal waters of New Mexico as compiled and interpreted by C.A. Swanberg.
7. Oxygen isotope shifts for New Mexico geothermal waters as determined by G.P. Landis in unpublished data.
8. Temperature gradient inset: correlation of oil and gas well temperature data and detailed temperature-depth logs for the San Juan and Permian Basins interpreted by C.A. Swanberg and P. Morgan.
9. Geochemical inset: stiff diagram for thermal and nonthermal waters from the Valles Caldera interpreted by C.A. Swanberg on the basis of data provided by Goff et al. (1982).
10. Geochemical table: in-situ temperatures, estimated subsurface temperatures based on the SiO_2 and Na-K-Ca geothermometers, and oxygen and hydrogen isotopic shifts as interpreted by C.A. Swanberg based on data provided by Goff et al. (1982).

Map 3. Bouguer Gravity Map of New Mexico was completed in draft form in 1983 by G.R. Keller and L. Cordell and is being prepared for production.

Map 4. Composite Aeromagnetic Map of New Mexico was completed in draft form in 1983 by L. Cordell and is being prepared for production.

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Chapter 2

Regional Geothermal Assessment in the Otero County Area*

Introduction

The south central New Mexico study area is centered in Otero County and includes parts of Dona Ana County to the west; Sierra, Socorro, and Lincoln counties to the north; and Chaves County to the east (see Figure 2-1). This area contains several population centers (e.g., Alamogordo, Capitan, Carrizozo, Ruidoso, Tularosa, and White Sands) and three large military facilities (i.e., Fort Bliss, Holloman Air Force Base, and White Sands Missile Range).

Climatologically the area ranges from an arid desert valley to semi-arid mountain ranges. Land surface altitudes range from 4,000 feet on the desert valley floor to over 12,000 feet at the crest of Sierra Blanca Peak. The average annual temperature ranges from approximately 60°F in the desert areas to 50°F in the mountain ranges, while the mean annual precipitation ranges from about 10 to 25 inches in the deserts and mountains, respectively. The main physiographic feature of the area (see Figure 2-1) is a very large (approximately 120 miles long and 40 miles wide) intermountain basin, the Tularosa Basin, flanked by several large mountain systems, the Franklin-Organ-San Andres mountain chain on the west, the Hueco-Sacramento-Sierra Blanca-Carrizo-Jicarilla mountain chain on the east, and the Oscura Mountains and Chupadera Mesa on the north.

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Figure 2-1. Location map for the Otero County area in south central New Mexico surveyed for geothermal energy potential.

According to McLean (1970), thick unconsolidated and semi-consolidated deposits of Cenozoic age, which form the most important aquifers in the Tularosa Basin, get progressively thicker from east to west across the basin. Unconsolidated alluvium was encountered to a depth of 1,960 feet in the south central part of the basin and to a depth of 6,015 feet several miles to the northwest. The alluvium may be as much as 8,000 feet thick in the southwestern portion of the basin. The basin is closed with an almost imperceptible divide separating its southern boundary from the Hueco Basin in Texas. The floor of the basin slopes gently southward and contains many depressions, or playas, which have no drainage outlet. Precipitation on the mountain slopes surrounding the basin runs off in intermittent streams that drain toward the center of the basin or moves as near-surface groundwater flow through alluvial deposits in the bottom of the stream channels. Both conditions probably occur because at the apex of each alluvial fan some of the runoff infiltrates into the shallow groundwaters.

Accretion of the groundwater reservoirs occurs mainly during winter storms because the intense summer thunderstorms produce such high runoff rates with such short durations that little groundwater recharge occurs. Most of the runoff from the summer storms passes beyond the toes of the alluvial fans out onto the basin floor forming ephemeral lakes on the playas (i.e., dry lakes or alkali flats) thereby depositing by evaporation a layer of dissolved solids in these areas. Groundwater flow patterns are probably determined and controlled by the structure (i.e., the dip, strike, and fault patterns) of the bedrock (Paleozoic strata) which, generally, directly underlies the Cenozoic unconsolidated and semi-consolidated deposits.

The geomorphic setting is one of alternating mountain uplifts and elongated structural basins. Many of the mountains are uplifted and rotated Paleozoic fault blocks structurally controlled by general N-S, NW-SE, and NE-SW grains of structural weakness. Igneous intrusive and extrusive bodies are also found in the mountainous regions contained in the study area. A very large late-Quaternary basalt flow and several vents are located in the northern part of the Tularosa Basin, which is structurally formed by a down-dropped Paleozoic block(s) dipping to the west and/or southwest.

Tectonically, the western half of the study area is located within the southern Rio Grande Rift system as defined by Chapin (1971) and modified by Chapin and Seager (1975) and Seager and Morgan (1979). The rift is a north-south trending active thermo-tectonic system which is characterized by late-Pliocene to late-Quaternary faulting and volcanic activity, exceptionally deep basins, high heat flow, and numerous geothermal areas. The present topography of the study area is dominated by a late-Quaternary basalt flow overlying the northern part of a deep middle- to late-Cenozoic basin formed contemporaneously with surrounding mountain uplifts, all of which is superimposed upon late-Cretaceous to early-Cenozoic (Laramide Orogeny) structural features and a variety of different tectonic features of middle-Tertiary age (Seager, 1975; Seager, 1981). Additional geological and geophysical data available for the study area include a residual Bouguer gravity map (Aiken et al., 1978), a lineament map (Lepley, 1982), fault maps (Clemons et al., 1982; Seager et al., 1983), and a large amount of temperature data.

Temperature Data

Actual Temperature Data

The actual temperatures of wells and springs are shown in Figure 2-2. The data were compiled from the USGS WATSTORE and GEOTHERM files. Additional temperature data were taken from McLean (1970) and Swanberg (1980b, 1980c). The data in the White Sands area were supplemented with temperature data reported by Kelly (1972), Kelly and Hearne (1976), Cruz (1982), and Kelley and Swanberg (1983). The data in the Hueco Tanks area, located just west of the Hueco Mountains in the south central part of the study area, were supplemented with temperature data from Taylor (1981) and Roy (1983). Temperature data for the Garton Well, located a few kilometers south of Holloman Air Force Base, were taken from Sprester (1980).

In order to increase the size of the data base, all temperatures recorded from depths less than 175 meters were included in Figure 2-2. Data from depths greater than 175 meters were excluded so that areas shown to be anomalous in Figure 2-2 were not the result of normal temperature data from exceptionally deep wells. Actual temperatures of a relatively small number of wells of unknown depth are also included in Figure 2-2. Comparison of bottom-hole formation data for these wells with the corresponding data from surrounding wells suggest that these wells are less than 175 meters deep.

Data from approximately 350 locations were screened for anomalous temperatures and analyzed for warming trends and patterns. Actual temperature data range from approximately 10 to 70°C, with 9 sites having temperatures greater than 30°C and 33 sites exhibiting tempera-

Figure 2-2. Actual temperatures ($^{\circ}\text{C}$) of springs and wells in the Otero County area. Surface temperatures are reported for springs. All well temperatures are recorded at depths less than 175 meters. The data are compiled from the USGS WATSTORE and GEOTHERM files, McLean (1970), Swanberg (1980b, 1980c), Kelly (1972), Kelly and Hearne (1976), Cruz (1982), Kelley and Swanberg (1983), Taylor (1981), Roy (1983), and Sprester (1980).

tures between 25 and 30°C. All of the sites with temperatures greater than 30°C are located in the Hueco Tanks area, except for the Garton Well which is located just south of Holloman Air Force Base. This well is artesian and the original flow, according to Sprester (1980), is reported to have been 1,100 gpm with a temperature of at least 30°C coming from an open cavity at 270 meters. An attempt to remove the well casing in 1937 broke the upper portion of the casing and led to cratering within the well. The temperature and flow rate has steadily decreased since 1937 probably due to a gradual plugging of the uncased upper portion of the well. Current reports of the temperature at the wellhead range from 24 to 33°C. The current estimate of the flow rate of the well is less than 10 gpm.

Bottom-Hole Temperature Gradient Data

In order to identify areas of elevated temperatures, bottom-hole temperature gradients were computed for approximately 265 locations with temperature data recorded from depths greater than 10 meters. The cutoff depth of 10 meters was used in order to avoid near-surface temperature disturbances caused by diurnal and annual temperature variations. The bottom-hole temperature gradients, which are shown in Figure 2-3 and tabulated in Table 2-1, were calculated using bottom-hole temperature and depth data and an assumed surface temperature of 20°C. The bottom-hole temperature and depth data from which the bottom-hole temperature gradients were calculated were taken from the USGS GEOTHERM file, Swanberg (1980b), and McLean (1970). The data in the White Sands area was supplemented with data reported by Kelly (1972), Kelly and Hearne (1976), Cruz (1982), and Kelley and Swanberg (1983), while the data for the Hueco Tanks area were supplemented by information from Tay-

Figure 2-3. Bottom-hole temperature gradients ($^{\circ}\text{C}/\text{km}$) of wells in the Otero County area for an assumed surface temperature of 20°C . The data are compiled from the USGS GEOTHERM file, Swanberg (1980b), McLean (1970), Kelly (1972), Kelly and Hearne (1976), Cruz (1982), Kelley and Swanberg (1983), Taylor (1981), Roy (1983), and Sprester (1980).

Table 2-1. Computed bottom-hole temperature gradients for wells in south central New Mexico.

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
<u>Dona Ana</u>	32°04.4'	106°26.1'	26	259	23	1
	32°16.7'	106°25.2'	25.5	139	39	1
	32°16.9'	106°25.1'	26.6	172	38	6,7 (T-17)
	32°16.9'	106°25.2'	32	531	23	3
	32°16.9'	106°25.2'	30	320	31	2
	32°17.3'	106°21.4'	23.7	75	49	4 (B-44)
	32°17.3'	106°28.3'	26	201	30	3
	32°19.2'	106°25.1'	25	95	53	6 (T-16)
	32°20.3'	106°27.7'	32.2	190	64	4 (T-18)
	32°21.2'	106°27.8'	24.2	100	42	4 (OWF-9)
	32°21.2'	106°25.7'	27	204	34	6,7 (T-15)
	32°21.4'	106°25.8'	33	504	26	3
	32°22.3'	106°26.8'	28.3	550	15	3
	32°22.4'	106°29.8'	25	244	20	3
	32°22.6'	106°28.4'	25.5	223	24	1
	32°22.6'	106°28.4'	25	212	23	1
	32°22.6'	106°29.9'	24	555	7	6 (T-12)
	32°22.8'	106°28.5'	24.7	160	29	4 (SW-21)
	32°22.9'	106°28.4'	28	223	35	1
	32°23.0'	106°29.0'	24.5	154	29	1
	32°23.0'	106°29.4'	19.5	152	-3	1
	32°23.1'	106°27.6'	24	107	37	1
	32°23.1'	106°27.6'	23	101	30	6 (T-5)
	32°23.1'	106°30.3'	22.2	174	13	3
	32°23.1'	106°30.6'	20.8	55	15	4 (B-21)
	32°23.2'	106°29.0'	26.5	251	25	1
	32°23.2'	106°29.0'	24	132	30	1
	32°23.3'	106°27.0'	26.5	244	27	6,7 (T-11)
	32°23.3'	106°29.4'	24.4	154	29	3
	32°23.3'	106°29.4'	26.1	251	24	3
	32°23.3'	106°29.4'	23.9	183	21	3
	32°23.3'	106°29.4'	24.4	247	18	3
	32°23.3'	106°29.4'	25.6	250	22	3
	32°23.5'	105°07.5'	20	155	0	1
	32°23.5'	106°28.4'	25.6	95	59	4 (B-12)
	32°23.5'	106°29.5'	25.5	270	20	1
	32°23.6'	106°31.1'	22.2	157	14	3
	32°23.7'	106°29.8'	24	247	16	6 (SW-14)
	32°23.8'	106°25.0'	54.4	1853	19	3
	32°23.8'	106°29.5'	24.5	247	18	1
	32°23.8'	106°29.7'	23.3	163	20	3
	32°23.8'	106°30.9'	24.5	157	29	6,7 (T-6)

Table 2-1. (Continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
<u>Dona Ana</u>	32°23.9'	106°30.0'	20	128	0	5 (B-20)
	32°23.9'	106°24.9'	25.1	95	54	4 (T-14)
	32°24.0'	106°26.6'	28	101	59	1
	32°24.2'	106°28.2'	28	295	27	1
	32°24.3'	106°20.8'	25.2	95	55	4 (Gregg)
	32°24.3'	106°28.3'	26.6	264	25	1
	32°24.3'	106°28.4'	27	305	23	6,7 (T-7)
	32°24.3'	106°28.4'	26.7	105	64	3
	32°24.5'	106°28.2'	28	305	26	1
	32°24.6'	106°29.8'	26.7	317	21	3
	32°24.6'	106°29.9'	24.5	190	24	6 (T-8)
	32°24.9'	106°24.9'	22.6	65	40	4 (B-14)
	32°25.1'	106°27.4'	27	169	41	6,7 (T-10)
	32°25.1'	106°29.2'	26.7	182	37	3
	32°25.2'	106°26.5'	22	95	21	6 (T-4)
	32°25.2'	106°27.6'	27.8	169	46	3
	32°25.2'	106°27.6'	25	166	30	1
	32°25.2'	106°28.4'	24.5	75	60	4 (B-24)
	32°25.3'	106°29.5'	24.7	95	49	4 (T-9)
	32°26.4'	106°25.2'	22.7	70	39	4 (B-16)
	32°26.6'	106°26.7'	26	159	37	1
	32°26.7'	106°26.6'	29	240	37	2
	32°26.7'	106°21.3'	21	55	18	5 (B-26)
	32°26.7'	106°26.8'	29.4	214	44	3
	32°27.5'	106°27.4'	28	174	46	3
	32°27.5'	106°27.7'	28.5	177	48	6,7 (SMR-4)
	32°27.7'	106°27.1'	29	310	29	2
	32°27.9'	106°26.6'	24.5	153	29	6 (T-13)
	32°28.0'	106°24.5'	22.3	65	35	4 (B-18)
	32°28.2'	106°30.0'	22.2	76	29	3
	32°28.3'	106°30.3'	25.5	76	72	6,7 (HTA-1)
	32°28.5'	106°23.8'	22	203	10	6 (SMR-5)
	32°28.5'	106°23.9'	22	203	10	3
	32°28.5'	106°26.7'	29	232	38	1
	32°28.6'	106°24.8'	24.5	12	62	1
	32°28.6'	106°30.8'	20.6	40	15	3
	32°28.7'	106°26.7'	28.9	232	38	3
	32°28.9'	106°25.2'	24.4	72	61	3
	32°28.9'	106°26.7'	26.5	144	45	1
	32°29.2'	106°26.7'	27.9	165	48	4 (SMR-2)
	32°29.4'	106°21.1'	20.5	50	10	5 (B-27)
	32°30.4'	106°25.9'	26	144	42	6,7 (SMR-1)
	32°30.5'	106°24.3'	21	55	18	5 (B-28)
	32°30.7'	106°17.9'	22	53	38	5 (B-39)

Table 2-1. (Continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
<u>Dona Ana</u>	32°31.6'	106°25.7'	26	305	20	6 (SMR-3)
	32°31.7'	106°25.6'	27.2	226	32	3
	32°32.0'	106°25.0'	32	300	40	2
	32°33.5'	106°21.4'	20.5	66	8	5 (B-31)
	32°33.5'	106°24.0'	21.5	58	26	5 (B-30)
	32°35.4'	106°17.6'	21	61	16	5 (B-38)
	32°37.2'	106°25.8'	26.5	228	28	1
	32°38.3'	106°28.2'	27.8	225	35	3
	32°38.8'	106°26.5'	26.7	215	31	3
	32°38.9'	106°27.4'	26	198	30	1
	32°51.9'	106°30.1'	26.7	225	30	3
<u>Lincoln</u>	33°08.7'	104°57.8'	18	55	-36	1
	33°13.7'	105°14.5'	16	191	-20	1
	33°16.4'	105°10.3'	18	175	-11	1
	33°16.6'	105°11.9'	16.5	201	-17	1
	33°18.0'	105°14.0'	16.5	82	-42	1
	33°18.8'	105°27.7'	16	198	-20	1
	33°19.1'	105°05.8'	16.5	38	-91	1
	33°19.4'	105°11.8'	17	47	-63	1
	33°19.5'	105°02.9'	18	38	-52	1
	33°19.6'	105°07.1'	16	53	-75	1
	33°19.8'	105°03.0'	18.5	73	-20	1
	33°20.0'	105°18.2'	16	43	-92	1
	33°20.0'	105°40.0'	13	36	-192	1
	33°20.2'	105°19.9'	17	81	-37	1
	33°20.5'	105°21.8'	16	98	-41	1
	33°20.5'	105°24.9'	21	125	8	1
	33°20.7'	105°17.8'	16	19	-208	1
	33°20.9'	105°17.1'	16	17	-234	1
	33°21.2'	105°16.7'	21	29	34	1
	33°21.2'	105°18.0'	16.5	34	-102	1
	33°21.7'	105°13.5'	16	21	-192	1
	33°21.8'	105°23.6'	17	64	-46	1
	33°21.9'	105°10.9'	16	25	-162	1
	33°22.0'	105°12.6'	15	30	-164	1
	33°22.0'	105°14.2'	16.5	21	-164	1
	33°22.1'	105°42.4'	9.5	20	-529	1
	33°22.6'	105°26.0'	22	244	8	1
	33°22.6'	106°02.1'	20	91	0	1
	33°23.1'	105°14.8'	18	38	-52	1
	33°23.3'	105°55.5'	16.7	91	-36	3
	33°23.4'	105°55.6'	16.5	91	-38	1
	33°23.5'	105°55.8'	16.5	91	-38	1
	33°23.9'	105°54.9'	16	14	-291	1

Table 2-1. (Continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient*	Source**
					(°C/km)	
<u>Lincoln</u>	33°23.9'	105°59.5'	18.3	72	-24	3
	33°24.1'	105°59.6'	18.5	72	-20	1
	33°24.4'	105°55.1'	16.7	17	-194	3
	33°24.5'	105°55.3'	16.5	17	-208	1
	33°24.6'	105°17.4'	16	23	-172	1
	33°25.1'	105°18.3'	16	36	-110	1
	33°26.0'	105°08.0'	21	111	8	1
	33°26.0'	106°26.8'	20	17	0	1
	33°26.1'	105°16.2'	18	43	-46	1
	33°26.7'	105°16.8'	19.5	67	-7	1
	33°26.7'	105°57.5'	15.5	13	-7	1
	33°27.0'	105°02.7'	19.5	107	-4	1
	33°27.2'	105°11.8'	17	172	-17	1
	33°27.8'	105°54.1'	13.5	67	-96	1
	33°27.9'	105°54.0'	13.3	67	-100	3
	33°28.0'	105°39.2'	10.5	18	-519	1
	33°28.3'	106°01.8'	18.5	27	-54	1
	33°28.3'	106°01.8'	18.3	30	-57	3
	33°28.4'	105°55.0'	15	35	-143	3
	33°28.4'	105°55.1'	15	35	-143	1
	33°28.9'	106°03.3'	21	41	24	1
	33°29.1'	106°03.3'	21.1	41	27	3
	33°29.1'	106°03.3'	25	29	172	3
	33°29.1'	106°04.8'	19.5	27	-18	1
	33°29.1'	106°04.8'	23	18	164	1
	33°29.2'	105°15.3'	19	107	-9	1
	33°29.2'	106°05.0'	22.8	15	187	3
	33°29.2'	106°05.0'	19.4	27	-22	3
	33°29.3'	105°14.6'	18	27	-72	1
	33°29.3'	105°22.9'	14	54	-111	1
	33°29.4'	105°23.1'	17	34	-89	1
	33°29.5'	106°01.1'	18.5	29	-51	1
	33°29.7'	105°07.5'	18.5	24	-63	1
	33°29.8'	106°01.3'	18.3	29	-59	3
	33°30.0'	106°10.1'	18.3	61	-28	3
	33°30.2'	105°19.0'	16	122	-32	1
	33°30.4'	106°07.6'	22	81	24	1
	33°30.7'	106°06.3'	22.2	81	27	3
	33°31.0'	105°58.1'	19	37	-27	1
	33°31.3'	105°28.1'	12	37	-218	1
	33°31.4'	105°08.8'	18.5	66	-22	1
	33°32.3'	106°12.9'	16.5	79	-44	1
	33°32.4'	105°57.1'	17	70	-42	1
	33°32.4'	106°02.9'	16.7	79	-42	3

Table 2-1. (Continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
<u>Lincoln</u>	33°32.4'	106°12.9'	19.5	62	-8	1
	33°32.5'	105°10.1'	16	27	-145	1
	33°32.6'	105°22.5'	15	122	-41	1
	33°32.6'	105°34.1'	15	98	-51	1
	33°32.7'	105°58.9'	23	18	164	1
	33°32.7'	106°12.8'	19.4	90	-7	3
	33°33.3'	106°07.5'	20	40	0	1
	33°33.6'	105°56.1'	18	21	-93	1
	33°33.7'	106°00.0'	19	23	-43	1
	33°33.7'	106°07.5'	20	102	0	3
	33°33.9'	105°55.1'	21.5	30	49	1
	33°34.2'	105°56.9'	17	20	-151	1
	33°34.7'	105°42.7'	14	66	-90	1
	33°34.7'	105°42.9'	14.5	91	-60	1
	33°34.8'	106°01.4'	20	15	0	3
	33°34.9'	106°01.4'	20	15	0	1
	33°35.4'	105°28.5'	14.5	27	-205	1
	33°35.4'	105°53.8'	19.5	91	-5	1
	33°35.6'	105°52.3'	16	68	-58	1
	33°35.9'	105°56.2'	16.7	54	-61	3
	33°36.1'	105°42.7'	16	38	-104	1
	33°36.7'	105°46.6'	13.5	79	-82	1
	33°36.9'	105°52.1'	19.5	43	-11	1
	33°37.1'	105°44.0'	15.5	30	-147	1
	33°37.1'	105°52.1'	19.5	43	-11	1
	33°37.8'	106°14.2'	17.2	48	-58	3
	33°37.9'	106°14.4'	17	46	-65	1
	33°37.9'	105°54.0'	14.5	23	-240	1
	33°38.3'	105°44.5'	15.5	38	-118	1
	33°38.4'	105°47.5'	16	38	-104	1
	33°38.9'	105°50.5'	15.5	21	-210	1
	33°39.3'	105°51.8'	15.5	18	-246	1
	33°40.1'	105°55.2'	16.5	14	-255	1
	33°40.2'	106°07.8'	20	113	0	1
	33°48.6'	105°58.3'	15.5	30	-147	1
	33°49.0'	105°58.9'	16	30	-109	1
	33°49.1'	105°57.4'	16.5	52	-66	1
	33°49.2'	105°57.0'	16.7	52	-63	3
	33°49.2'	105°57.0'	16	46	-87	3
	33°49.4'	106°26.2'	17	55	-54	1
<u>Otero</u>	31°58.6'	106°04.5'	28.4	50	167	8 (HT-10)
	31°58.6'	106°07.1'	24.6	49	93	8 (HT-6)

Table 2-1. (Continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
Otero	31°59.2'	106°03.8'	22.9	49	60	8 (HT-14)
	31°59.5'	106°05.6'	35.1	50	301	8 (HT-9)
	31°59.5'	106°06.2'	66.6	300	155	8 (HT-12)
	31°59.5'	106°06.2'	65.8	291	157	9 (HT-12)
	31°59.7'	106°06.0'	45.5	120	213	8 (HT-11)
	31°59.8'	106°07.0'	27.7	49	157	8 (HT-5)
	31°59.9'	106°05.3'	32.5	50	249	8 (HT-8)
	32°00.0'	106°06.7'	34.3	47	304	8 (HT-7)
	32°00.0'	106°07.3'	26.6	49	134	8 (HT-4)
	32°00.0'	106°07.9'	27.2	49	146	8 (HT-3)
	32°00.0'	106°08.5'	24.9	47	103	8 (HT-2)
	32°00.0'	106°08.8'	24.4	50	88	8 (HT-1)
	32°00.0'	106°11.0'	22.1	50	42	8 (HT-13)
	32°00.8'	105°08.9'	20	136	0	1
	32°01.0'	105°06.9'	21.5	120	12	1
	32°01.0'	105°08.4'	20	76	0	1
	32°01.1'	105°07.9'	20.5	101	4	1
	32°01.1'	105°28.5'	21	46	21	1
	32°01.1'	106°06.6'	22.1	50	42	8 (HT-15)
	32°01.2'	105°19.8'	21	183	5	1
	32°01.6'	105°06.3'	22	130	15	1
	32°01.6'	106°03.3'	11.5	116	-73	1
	32°01.6'	106°18.3'	22.2	116	19	3
	32°01.8'	106°03.2'	24.1	50	83	8 (HT-22)
	32°02.0'	105°06.1'	21.5	32	46	1
	32°02.3'	105°41.9'	21	198	5	1
	32°02.4'	106°07.4'	74	459	117	9 (MG-16)
	32°02.6'	105°36.8'	20	197	0	1
	32°02.7'	106°02.7'	38.3	50	365	8 (HT-18)
	32°02.7'	106°05.2'	23.7	48	73	8 (HT-16)
	32°03.3'	106°06.5'	22.7	50	53	8 (HT-17)
	32°03.4'	105°12.0'	20	96	0	1
	32°03.8'	106°09.1'	71.1	137	373	3
	32°04.1'	106°02.4'	25.2	45	116	8 (HT-19)
	32°04.2'	106°09.1'	71	140	364	2
	32°04.5'	106°05.9'	17	182	-16	1
	32°04.5'	106°06.2'	20.6	182	3	3
	32°04.5'	106°10.7'	50	133	226	3
	32°04.7'	106°10.5'	33.5	142	95	1
	32°05.0'	106°09.4'	61	230	178	2
	32°04.7'	106°07.2'	22.4	48	51	8 (HT-21)
	32°04.7'	106°09.3'	71.5	304	169	9 (MG-14)
	32°04.9'	106°09.1'	61.1	227	181	3

Table 2-1. (Continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
<u>Otero</u>	32°05.0'	106°09.0'	61	227	180	1
	32°05.0'	106°09.4'	61	230	178	2
	32°05.4'	106°02.9'	25.3	50	106	8 (HT-20)
	32°05.7'	105°05.3'	20	24	0	1
	32°05.8'	106°04.7'	28.7	50	174	8 (HT-26)
	32°06.2'	105°04.8'	22	335	5	1
	32°06.3'	105°36.1'	20.5	117	4	1
	32°06.4'	105°04.9'	16	43	-93	1
	32°06.8'	106°03.5'	24.5	50	91	8 (HT-24)
	32°06.8'	106°20.1'	26.5	134	48	1
	32°07.2'	106°06.7'	25.7	50	115	8 (HT-23)
	32°07.4'	106°05.1'	26.4	50	129	8 (HT-25)
	32°08.0'	105°08.0'	18.5	21	-70	1
	32°08.2'	105°39.1'	20.5	32	15	1
	32°09.0'	105°12.9'	20.5	137	3	1
	32°09.2'	105°22.5'	19.5	198	-2	1
	32°10.1'	105°03.0'	18	27	-72	1
	32°10.3'	105°37.9'	18.5	117	-12	1
	32°10.8'	105°35.4'	18	213	-9	1
	32°12.7'	105°02.4'	18.5	42	-35	1
	32°15.0'	105°25.7'	19	213	-4	1
	32°16.7'	105°07.8'	20.5	90	5	1
	32°17.9'	105°26.4'	28	183	43	1
	32°20.7'	105°26.3'	21.5	290	5	1
	32°22.7'	105°39.5'	20.5	288	1	1
	32°23.3'	105°55.9'	19	31	-32	1
	32°24.3'	106°20.7'	26	152	39	1
	32°24.3'	106°20.8'	25.6	146	38	3
	32°25.0'	106°07.0'	41	600	35	2
	32°29.1'	105°09.2'	18.5	58	-25	1
	32°30.0'	106°06.0'	32	370	32	2
	32°38.1'	106°19.7'	21	63	15	1
	32°40.0'	106°07.3'	18	21	-93	1
	32°40.4'	106°09.4'	16.5	21	-164	1
	32°41.0'	106°10.2'	16.5	16	-220	1
	32°44.3'	105°28.7'	14	85	-70	1
	32°46.5'	106°08.5'	36	271	59	10 (Garton)
	32°47.1'	105°56.1'	26.7	561	12	3
	32°47.8'	105°59.0'	19	85	-11	1
	32°48.6'	105°58.0'	18	83	-24	1
	32°48.7'	105°58.1'	21	74	13	1
	32°48.8'	105°57.6'	21.1	62	18	3
	32°48.8'	105°57.6'	21.1	53	21	3

Table 2-1. (Continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
Otero	32°48.8'	105°57.6'	22.2	79	79	3
	32°48.8'	105°57.6'	21.7	73	23	3
	32°48.8'	105°57.6'	21.4	113	15	3
	32°48.8'	105°58.1'	19.5	72	-6	1
	32°48.8'	105°58.7'	21	23	43	1
	32°49.0'	105°57.4'	21	61	16	1
	32°49.0'	105°58.6'	21.1	83	13	3
	32°49.0'	105°58.6'	22.8	70	40	3
	32°49.0'	105°58.6'	21.1	78	14	3
	32°49.0'	105°58.6'	21.1	72	15	3
	32°49.0'	105°58.6'	20	74	0	3
	32°49.2'	105°56.8'	21	76	13	1
	32°49.3'	105°57.4'	21	76	-6	1
	32°49.4'	105°56.8'	21.7	76	22	3
	32°50.7'	105°58.0'	19.5	82	-6	1
	32°51.0'	105°57.8'	18.9	43	-26	3
	32°51.0'	105°57.8'	19.4	82	-7	3
	32°51.1'	105°57.6'	19	43	-23	1
	32°52.0'	105°59.0'	19.5	46	-10	1
	32°53.0'	105°57.2'	19	82	-12	1
	32°53.4'	105°59.6'	20	61	0	1
	32°53.5'	105°59.8'	20	61	0	3
	32°53.6'	106°09.0'	19.5	64	-7	1
	32°54.0'	106°08.8'	18	27	-75	1
	32°54.0'	106°08.8'	17.8	27	-81	3
	32°54.0'	106°08.8'	19.4	64	-9	3
	32°55.2'	106°04.1'	20.5	121	-37	1
	32°55.4'	106°04.0'	20.8	123	7	3
	32°55.5'	106°08.8'	19	27	-37	1
	32°55.8'	106°08.7'	18.9	26	-42	3
	32°57.0'	106°01.3'	20.6	126	5	3
	32°56.3'	105°45.0'	8	131	-91	1
	32°56.4'	106°02.5'	19	123	-8	1
	32°57.0'	105°42.2'	9	59	-185	1
	32°57.0'	106°00.0'	20	61	0	1
	32°57.1'	106°01.3'	20.5	126	3	1
	32°58.5'	105°25.4'	14	62	14	1
	32°58.8'	105°56.0'	14	156	-38	1
	32°59.9'	106°01.6'	20.5	46	10	1
	33°02.7'	106°03.4'	18.9	125	-9	3
	33°02.8'	106°01.7'	16.5	64	-54	1
	33°02.9'	106°03.2'	19	125	-8	1
	33°03.3'	106°00.9'	15	70	-71	3

Table 2-1. (Continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
<u>Otero</u>	33°03.3'	106°01.1'	15	70	-71	1
	33°03.8'	106°03.0'	17.8	61	-36	3
	33°03.8'	106°03.0'	24	396	10	3
	33°04.1'	106°03.0'	17	61	-49	1
	33°04.3'	106°00.3'	14.5	67	-82	1
	33°04.5'	106°00.2'	15	116	-42	1
	33°04.6'	106°02.5'	17.8	71	-31	3
	33°04.7'	106°00.2'	15.5	116	-38	1
	33°05.6'	105°29.0'	13	135	-51	1
	33°05.7'	106°00.6'	15.5	102	-43	1
	33°06.6'	105°34.2'	11	89	-100	1
	33°07.9'	105°25.2'	17	94	-31	1
	33°08.8'	106°02.0'	23.3	82	40	3
	33°10.3'	105°25.5'	13.5	128	-50	1
	33°10.6'	105°20.0'	11	63	-143	1
	33°10.6'	106°04.0'	13	29	-241	1
	33°11.3'	105°40.3'	12	216	-36	1
	33°13.0'	105°49.6'	16.5	198	-17	1
	33°13.1'	105°26.3'	15	192	-25	1
	33°13.5'	105°37.2'	9.5	70	-149	1
	33°15.1'	105°39.9'	11	119	-75	1
	33°15.1'	105°43.1'	13.5	143	-45	1
	33°16.7'	105°18.1'	20	140	0	1
	33°16.9'	105°29.3'	14.5	189	-29	1
	33°17.6'	105°20.3'	16	190	-21	1
	33°18.9'	105°58.9'	21	18	54	1
	33°19.5'	106°03.4'	21.1	18	61	3
	33°20.0'	105°59.3'	20.5	48	10	1
	33°20.5'	105°55.8'	19.5	31	-16	1
	33°20.7'	106°04.2'	20.6	48	13	3
	33°20.9'	105°54.8'	20	116	0	3
	33°21.7'	105°55.1'	17	17	-178	1
	33°21.7'	105°59.7'	18	91	-21	1
	33°21.8'	105°56.0'	24	42	95	1
	33°21.9'	105°55.8'	17.2	17	-165	3
	33°21.9'	105°55.8'	23.9	42	93	3
	33°22.0'	105°56.5'	19.5	13	-37	1
	33°22.3'	105°56.2'	16.5	35	-98	1
	33°22.6'	105°56.5'	16.7	35	-94	3
	33°22.6'	105°56.5'	18.3	78	-22	3
	33°22.6'	105°56.5'	17.8	91	-24	3
	33°22.8'	105°55.3'	17.8	91	-24	3
	33°22.8'	105°55.3'	18.3	91	-19	3

Table 2-1. (Continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)	Source**
<u>Otero</u>	33°23.0'	105°55.5'	13	61	-114	1
	33°23.3'	105°55.5'	18.9	31	-35	3
<u>Sierra</u>	32°59.7'	106°32.6'	18.3	22	-77	3
	33°04.1'	106°25.8'	14	152	-39	1
	33°19.5'	106°24.4'	24.5	109	41	1
	33°19.5'	106°35.2'	20	38	0	3
	33°26.1'	106°26.7'	20	15	0	3
<u>Socorro</u>	33°34.0'	106°01.5'	21.7	70	24	3
	33°34.1'	106°27.3'	24.4	76	57	1
	33°34.2'	106°27.0'	21	73	13	1
	33°40.0'	106°05.6'	17	40	-75	1
	33°40.4'	106°08.8'	20	113	0	3
	33°42.8'	106°07.9'	20.5	216	2	1
	33°42.8'	106°08.0'	20.6	216	3	3
	33°45.2'	106°17.8'	15.6	62	-71	3
	33°45.2'	106°17.8'	15.8	64	-66	3
	33°45.5'	106°21.3'	7	2,277	-5	1
	33°45.6'	106°18.0'	18.5	67	-22	1
	33°45.9'	106°17.8'	15.5	20	-220	1
	33°46.0'	106°17.5'	14.7	62	-84	1
	33°46.3'	106°15.8'	25.8	96	60	3
	33°46.7'	106°16.3'	25	96	52	1
	33°51.7'	106°27.5'	19.5	58	-8	1
	33°52.1'	106°23.0'	13	96	-72	1
	33°52.7'	105°59.1'	18.9	49	-22	3

* Computed negative bottom-hole temperature gradients correspond to wells with bottom-hole temperatures less than the assumed surface temperature of 20°C.

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

- Sources:
1. USGS GEOTHERM file
 2. Swanberg (1980b)
 3. McLean (1970)
 4. Kelley and Swanberg (1983)
 5. Kelly (1972)
 6. Kelly and Hearne (1976)
 7. Cruz (1982)
 8. Taylor (1981)
 9. Roy (1983)
 10. Sprester (1980)

lor (1981) and Roy (1983). Temperature and depth data for the Garton Well were taken from Sprester (1980).

Geotemperature Data

Figures 2-4 and 2-5 show SiO_2 and Na-K-Ca geotemperature data, respectively. The SiO_2 data were taken from the USGS WATSTORE file and Swanberg (1980a, 1980c). The WATSTORE data are concentrated in the White Sands area and were supplemented with data from Kelley and Swanberg (1983). Data in the Hueco Tanks area (see insert, Figure 2-4) come from Hoffer (1979). The Na-K-Ca data were compiled from the WATSTORE file and Swanberg (1980a, 1980c).

Silica geotemperatures exist for 92 sites, excluding the Hueco Tanks area which contains 26 sites. In the Hueco Tanks area, SiO_2 geotemperatures range from 45 to 151°C. The majority of these geotemperatures fall in the 80 to 85°C range, with only four sites having values above 100°C. Sixty-one locations outside of the Hueco Tanks area have SiO_2 geotemperatures that indicate reservoir base temperatures of at least 60°C. Alkali (Na-K-Ca) geotemperatures are available for 69 sites, with 14 sites having geotemperatures that indicate reservoir base temperatures of at least 60°C.

Anomalous Temperature Data

Sites characterized by anomalous temperature data are shown in Figure 2-6. Actual temperatures equal to or greater than 25°C and bottom-hole temperature gradients equal to or greater than 40°C/km are considered anomalous within the study area. A visual examination of the anomalous data readily shows two distinct thermal regimes: (1) an anomalously warm crust dominating the western and southern portions of the study area and (2) a normal or cool crust predominate in the rest of

Figure 2-4. SiO₂ geotemperatures (°C) of springs and wells in the Otero County area. The data are compiled from the USGS WATSTORE file, Swanberg (1980a, 1980c), Kelley and Swanberg (1983), and Hoffer (1979).

Figure 2-5, Na-K-Ca geotemperatures ($^{\circ}\text{C}$) of springs and wells in the Otero County area. The data are compiled from the USGS WATSTORE file and Swanberg (1980a, 1980c).

Figure 2-6. Sites in the Otero County area characterized by anomalous actual temperatures ($\geq 25^{\circ}\text{C}$) of wells and springs and bottom-hole temperature gradients ($\geq 40^{\circ}\text{C/km}$) of wells.

the study area, where there is almost a total absence of anomalous data. The anomalous data which characterize the western and southern portions of the study area are typical of the normal temperature data found immediately to the west in the southern Rio Grande Rift system (Lohse, 1982), which suggests that this part of the study area is within the rift system. This view has been expressed previously by Chapin and Seager (1975) and Seager and Morgan (1979).

Major thermal anomalies are apparent in the southwest portion of the study area in the Hueco Tanks and White Sands areas. Much work has already been done in the Hueco Tanks area, which has been confirmed as a major low-temperature geothermal system (Taylor, 1981; Roy, 1983). A temperature contour map at 50 meters (Taylor, 1981) suggests that the anomaly is controlled by NW-SE and N-S trends of structural control. Actual temperature and bottom-hole temperature gradient data also show these same general trends and patterns (see Figures 2-2 and 2-3).

A second low-temperature system also appears to be present in the White Sands area; however, this system has not yet been confirmed at shallow depths. A temperature of 54°C at a depth of approximately 1,800 meters has been reported (McLean, 1970) in a well located several miles out in the basin which deepens abruptly due to the subsurface structure (i.e., steep faults, large offsets, and the strike and dip of the bedrock) in the area. A bottom-hole temperature of 92°C was repeatedly reported during testing of this well over a period of several months after drilling; however, the highest temperature that could be confirmed is 54°C . The well was plugged back to 113 meters immediately after completion of the original test (Doty and Cooper, 1970). The large range of actual temperatures and bottom-hole tempera-

ture gradients and the unordered pattern of these data (see Figures 2-2 and 2-3) in the White Sands area, which is a major groundwater recharge area for this portion of the basin, is attributed to the mixing of thermal and nonthermal fluids.

The actual temperature and bottom-hole temperature gradient data also show two distinct warming trends adjacent to the White Sands area. One of the areas is located approximately 8 to 16 kilometers north of White Sands and the other a few kilometers to the south. Additional anomalous areas shown in Figure 2-6 which may have low-temperature geothermal resources include the Garton Well area south of Holloman Air Force Base, a NE-SW band across the northwest part of the study area, and the Salinas Peak area.

Anomalous Geotemperature Data

Sites characterized by anomalous geotemperature data are shown in Figure 2-7. Values of the SiO_2 and Na-K-Ca geotemperatures equal to or greater than 60°C are considered anomalous.

Generally, in order for a specific site or locality to be considered as an anomalous area there should be general agreement between the predicted SiO_2 and Na-K-Ca geotemperatures. This criterion appears to be inappropriate for use within the study area for two reasons. First, Na-K-Ca geotemperatures are calculated for only some of the sites with SiO_2 geotemperatures. Secondly, even when Na-K-Ca geotemperatures are available, the results may be of limited value because many of the waters have been in contact with evaporites, which makes the Na-K-Ca geothermometer unreliable (Henry and Gluck, 1981). Consequently, a less restrictive methodology of considering not both, but either of the two geothermometers to be sufficient to classify an area or site as anomalous was used.

Figure 2-7. Sites in the Otero County area characterized by anomalous SiO₂ or Na-K-Ca geotemperatures ($\geq 60^{\circ}\text{C}$) of wells and springs.

The maximum temperature of a geothermal system may be estimated accurately only if the waters are in equilibrium with minerals that control dissolved concentrations and mixing with nonthermal water has not occurred (Fournier et al., 1974). According to Arnorson (1975), equilibrium with quartz occurs only in waters with temperatures in excess of 180°C, which is a condition not very likely to be satisfied within the study area. Secondly, dilution of the thermal waters has probably occurred because most of the sampled waters are cool groundwater elevated in temperature as the result of mixing with thermal waters (a possible exception to this condition might be the Hueco Tanks area). Because these conditions necessary for the accurate estimation of the maximum reservoir base temperature are not met strictly in the study area, the SiO_2 geothermometer will underestimate geothermal reservoir base temperatures. In addition, according to Henry (1979), the waters may be in equilibrium with chalcedony rather than quartz. This condition would result in the reservoir base temperature being overestimated by the SiO_2 (quartz) geothermometer. The net effect of these observations is believed to result in the underestimation of the reservoir base temperature predicted by the SiO_2 (quartz) geothermometer.

The area defined by anomalous geotemperature data is essentially the same as that represented by the anomalous actual temperature and bottom-hole temperature gradient data (see Figure 2-6), except for an additional area in the north central part of the study area. Anomalous geotemperature data are observed principally in the Hueco Tanks, White Sands, Garton Well, and the Salinas Peak areas (see Figure 2-7). In addition, anomalous data are found in the north central part of the

study area, extending northward from several kilometers to the southwest of Capitan through the Tuscon-Carrizo-Patos mountain area. This area is not characterized by anomalous actual temperature and bottom-hole temperature gradient data (see Figure 2-6) as are all of the other anomalous geotemperature areas shown in Figure 2-7. A single anomalous geotemperature value occurs in the southern part of Crow Flats in the southeast portion of the study area.

The Hueco Tanks area is the only anomalous area in which trends that control the anomalous geotemperatures may be deduced. In this area, the thermal anomaly defined by SiO_2 geotemperatures appears to be constrained by general N-S and NW-SE trends of structural control (see insert, Figure 2-4).

Geologic and Geophysical Data

Tectonic Features

Major tectonic features in the study area include mapped surface faults, a late-Quaternary basalt flow, and several associated volcanic vents (see Figure 2-8). The location and age of some dated basaltic rocks associated with the basalt flow (Allen, 1951) are also shown in Figure 2-8. The mapped faults in Dona Ana County and western Otero County are reproduced from Seager et al. (1983). All other faults have been abstracted from Clemons et al. (1982).

Most of the faults in the western one-third of the study area cut late-Quaternary surfaces. The most extensive and active late-Quaternary faulting is found in the southwest portion of the study area in the southern end of the Tularosa Basin and along the western boundary faults

Figure 2-8. Mapped surface faults, late-Quaternary volcanic rocks and vents, and locations and ages of dated basaltic rocks in the Otero County area. The data are taken from Clemons et al. (1982), Seager et al. (1983), and Allen (1951).

between the Organ Mountains and the Tularosa Basin. One of these young boundary faults in the White Sands area has been reported by Seager (1981) to cut a Holocene alluvial fan and is estimated to be less than 3,000 to 4,000 years old. Seager (1981) also pointed out that a history of repeated movement during the Quaternary Period along these west side basin boundary faults is indicated by the varying heights of fault scarps that cut at least five generations of alluvial fans. The late-Quaternary basalt flow and vents in the northern part of the Tularosa Basin have been dated at approximately 1,000 years, which makes this basalt flow one of the youngest in New Mexico and also suggests that the volcanism could be related to late-Quaternary faulting.

The geometrical shape and orientation of the uplifted fault blocks in the western portion of the study area (see Figures 2-1 and 2-8) suggest that the main grain of structural control is in a NNW-SSE direction. A fairly strong grain of structural control in a NNE-SSW direction is evidenced by the many faults throughout the study area which have this orientation (see Figure 2-8).

Another strong trend of structural control extends diagonally from the northwest to the southeast corner of the study area in a NNW-SSE direction. This trend is oriented some 15 to 20° more towards the northwest than the suspected main grain of structural control. A weaker trend is suspected along a NE-SW trend from the Organ Mountains-Bishop Cap area through the Jarilla Mountains and across the central portions of Otero and Chaves counties. This trend and other stronger parallel trends are also evident in the gravity data. A NW-SE trend is suspected in the southwest corner of the study area extending from the Organ

Mountains-Bishop Cap area through the southern portion of the Tularosa Basin into the Hueco Tanks thermal anomaly.

Lineament Data

Lineament data (Lepley, 1982) for the study area are shown in Figure 2-9. In general, the lineament data show the same trends and grains of weakness as the mapped surface faults (see Figure 2-8) with the exception that in the lineament data the NE-SW and NW-SE trends appear stronger, while the NNW-SSE and the NNE-SSW trends are less pronounced. The NNW-SSE diagonal trend from the northwest to the southeast corner of the study area appears very weak and is offset to the west in the southeast.

Gravity Data

The residual Bouguer gravity data of Aiken et al. (1978) are reproduced in Figure 2-10. Values of 5 mgal and larger are shown as highlighted contour lines to visually enhance the data. The main features displayed by the residual gravity data are: a regional low on the west side of the study area which is elongated in a N-S direction and associated with the Tularosa Basin; a regional high on the extreme west side of the study area which trends 5 to 10° west of north and is associated with the San Andres Mountains; a regional gravity maximum in the southwest corner of the study area coincident with the Bishop Cap-Franklin Mountain area; and a large regional high in the northern portion of the study area which strongly suggests both NW-SE and NE-SW structural control. Some less apparent features include NW-SE and NE-SW trends of structural control in the southern portion of the study area and approximately 10° east of north trends which extend from the

Figure 2-9. Lineament map of the Otero County area [from Lepley (1982)].

Figure 2-10. Residual Bouguer gravity map of the Otero County area [from Aiken et al. (1978)].

southwest corner of Otero County across the study area and which are apparent to a lesser degree on the far east side of the study area.

Discussion

All of the anomalous actual temperature, bottom-hole temperature gradient, and geotemperature data are synthesized in Figure 2-11. Locations where low-temperature geothermal resources are thought to exist are shown as shaded areas, which are constructed and oriented to display the subsurface structure thought to control each suspected low-temperature resource area. The orientation of the controlling subsurface structure is inferred mainly from residual gravity, tectonic (mapped surface faults), and anomalous temperature and geotemperature data and, to a lesser extent, from the lineament data. The spatial relationship between trends inferred by the residual gravity data, anomalous temperature and geotemperature data, and the mapped surface faults suggests fault-controlled hydrothermal systems as the principal controlling mechanism responsible for the low-temperature geothermal anomalies. Most of the major faults thought to be responsible for the control of the geothermal fluids are active late-Quaternary faults of a tensional nature evidenced by the normal faulting style.

The major low-temperature geothermal resources are found in the Hueco Tanks and the White Sands areas which are located in the southwest portion of the study area in the southern end of the Tularosa Basin. The Hueco Tanks area is by far the most thoroughly delineated of the anomalous areas. Much geological and geophysical work has already been performed by Taylor (1981) and Roy (1983), including detailed gravity and temperature gradient surveys. These data have been used in gravity

Figure 2-11. Locations in the Otero County area characterized by anomalous actual temperatures of springs and wells, bottom-hole temperature gradients of wells, and geotemperatures of springs and wells. Shaded areas indicate confirmed and potential low-temperature geothermal resource areas.

and heat flow models (Taylor, 1981) to constrain the parameters for the geothermal system. The results indicate a fault-controlled hydrothermal system with possible maximum temperatures of 140 to 150°C, based on SiO₂ geotemperatures. Taylor (1981) reported that geophysical models also predict similar temperatures at about a 3 kilometer depth, while only 80°C water is likely to exist within 1.5 kilometers of the surface. The deepest drill holes in this area are approximately 1,000 feet, which is an insufficient depth to verify the assumption by Taylor (1981) that these faults are isothermal to a depth of about 1.5 kilometers.

To date, very little geological or geophysical work has been carried out in the White Sands area for the purpose of delineating or confirming the existence of geothermal resources. Based upon anomalous temperature and geotemperature data, the area is highly suspected of containing a large low-temperature geothermal reservoir, especially considering that this area is known to be both a major groundwater recharge zone and characterized by active late-Quaternary faulting.

Other suspected low-temperature geothermal areas include the Salinas Peak area in the northwest part of the Tularosa Basin, a NE-SW trend across the northern end of the Tularosa Basin, and the Garton Well area located approximately 10 kilometers to the southwest of Holloman Air Force Base. The Garton Well area and several other small possible low-temperature resource areas to the north of Tularosa may be associated with eastern boundary faults of the Tularosa Basin. Two additional small possible low-temperature areas are located in the southeastern portion of the study area.

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Chapter 3

Regional Geothermal Exploration in North Central New Mexico

(Bernalillo, Los Alamos, Mora, Rio Arriba, San Miguel,
Sandoval, Santa Fe, Taos, Torrance, and Valencia Counties)

Part 1

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

Introduction

The study area (see Figure 3-1) is located in the north central part of New Mexico (see insert, Figure 3-1) 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

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Figure 3-1. Location map for the area in north central New Mexico surveyed for geothermal energy potential.

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 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.

Temperature Data

Actual Temperature Data

The actual temperatures of wells and springs are shown in Figure 3-2. 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 3-2. Data from depths greater than 150 meters were excluded so that areas shown to be anomalous in Figure 3-2 were not the result of normal temperature data from exceptionally deep wells.

Figure 3-2. 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).

Actual temperatures of a number of wells of unknown depth were also included in Figure 3-2. 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., $< 22.5^{\circ}\text{C}$) 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 3-3) 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

Figure 3-3. 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 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.

Bottom-Hole Temperature Gradients

Bottom-hole temperature gradients were calculated in order to identify areas within the crust which are characterized by elevated 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 3-3 and tabulated in Table 3-1. 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.

Geotemperature Data

Geotemperature data were compiled from the USGS WATSTORE file and Swanberg (1980a, 1980c). Figures 3-4 and 3-5 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.

Table 3-1. 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 3-1. (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 3-1. (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 3-1. (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 3-1. (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 3-1. (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 3-1. (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 3-1. (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 3-1. (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 3-1. (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 3-1. (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 3-1. (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°07.3'	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 (PEÑASCO)
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 3-1. (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 3-4. 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 3-5. Na-K-Ca geotemperatures ($^{\circ}\text{C}$) of springs and wells in north central New Mexico. The data are compiled from the USGS WATSTORE file and Swanberg (1980a, 1980c).

Anomalous Temperature Data

Sites characterized by anomalous temperature data are shown in Figure 3-6. Actual temperatures greater than or equal to 22.5°C and bottom-hole temperature gradients greater than or equal to $45^{\circ}\text{C}/\text{km}$ are considered anomalous within the study area. In general, the main area characterized by both anomalous actual temperatures and bottom-hole temperature gradients is centered within and around the Albuquerque-Belen Basin (compare Figures 3-1 and 3-6). The actual temperature data (see Figure 3-2) suggests that the study area is composed of two thermal regimes. This observation is supported by the fact that there is almost a total absence of actual temperatures less than 15°C in the southwest portion of the study area. Although the data are not as uniform or dense, Figure 3-3 generally shows the same pattern indicated by the near absence of negative bottom-hole temperature gradient values (negative bottom-hole temperature gradients result when bottom-hole temperatures are less than the assumed surface temperature of 15°C). In addition, Figure 3-3 also suggests that the southwest part of Rio Arriba County (see Figure 3-1) may be anomalously warm with respect to adjacent parts of the study area. Other major areas of anomalous temperature data are located in the northeast portion of the study area near Ojo Caliente and approximately 35 kilometers to the northeast of Ojo Caliente (compare Figures 3-1 and 3-6).

By examining Figures 3-2, 3-3, and 3-6 together, additional information may be obtained about the anomalous areas. In the extreme southern end of the study area, near Socorro, there are numerous sites that have anomalous bottom-hole temperature gradients but few sites that have anomalous actual temperatures. Figure 3-3 shows that the anomalous

Figure 3-6. 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.

bottom-hole temperature gradients are generally greater than $120^{\circ}\text{C}/\text{km}$ within and to the north of the Socorro area and generally between 45 and $90^{\circ}\text{C}/\text{km}$ toward the northwest. The absence of numerous anomalous actual temperature data in this area is attributed to the very shallow depths (i.e., bottom-hole depths) from which the temperatures are taken. 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 3-1) is another area of interest. This area

is characterized by anomalous actual temperature data but no anomalous bottom-hole temperature gradient data (see Figure 3-6). Figure 3-2 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 3-6 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 3-1 and 3-2). Inspection of Table 3-1 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 $30^{\circ}\text{C}/\text{km}$. 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 $30^{\circ}\text{C}/\text{km}$ 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 3-6). Figure 3-2 shows that the actual temperatures are in the range of 22.5 to 30°C and the data of Figure 3-3 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 3-3). Inspection of Table 3-1 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 3-1 and 3-6). 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 3-2, 3-3, and 3-6 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 3-1 and 3-6). 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 3-3).

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 3-1 and 3-6). 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 3-1 and 3-6) are believed to be from deep depths (see Figure 3-3) 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 .

Anomalous Geotemperature Data

Anomalous geotemperature data are shown in Figure 3-7. 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 3-7 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 3-4 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

Figure 3-7. Sites in north central New Mexico characterized by anomalous SiO_2 ($\geq 60^{\circ}\text{C}$) and Na-K-Ca ($\geq 70^{\circ}\text{C}$) geotemperatures of springs and wells.

anomalous Na-K-Ca geotemperature data (see Figure 3-5), with the exception of the Ojo Caliente area and a small area located 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 3-6), as well as with respect to SiO_2 geotemperature data (see Figure 3-4).

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 3-1 and 3-7). 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 3-4 and 3-5).

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.

Geologic and Geophysical Data

Tectonic Data

Figure 3-8 shows two periods of late-Cenozoic faulting: faults that cut late-Pliocene to Pleistocene (~1 to 4 m.y. old) surfaces and faults that cut late-Quaternary (<1 m.y. old) surfaces. Also shown in Figure 3-8 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 3-8 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 3-9. Also shown in Figure 3-9 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 3-8. 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

Figure 3-8. Late-Cenozoic faults and major volcanic centers in north central New Mexico. The data are taken from Callender and Seager (1980).

Figure 3-9. Ages of dated volcanic rocks in north central New Mexico. The data are taken from Aldrich and Laughlin (1981).

position of the caldera and the associated high-temperature hydrothermal system. The other NE-SW trend cuts across Bernalillo and Valencia counties.

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 3-1 and 3-9). 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.

Gravity Data

The residual gravity data (Aiken et al., 1978) for the study area are contoured at 5-mgal intervals (see Figure 3-10). 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,

Figure 3-10. Residual Bouguer gravity map of north central New Mexico [from Aiken et al. (1978)].

situated on the east central portion of the regional residual gravity high, that is associated with the uplifted Paleozoic and Precambrian 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 3-1 and 3-10) 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 3-10).

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/cm^3) 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.

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 3-11 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 3-11), the late-Cenozoic faulting patterns (see Figure 3-8), and the major gravity gradients associated with west-side basin boundary faults and the NE-SW grains correlated with the Jemez Lineament (see Figure 3-10). 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 3-8 and 3-9, respectively), coupled with the presence of an anomalous thermal regime (see Figure 3-11), 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 3-11. 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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Part 2

Measured Geothermal Gradients in North Central New Mexico*

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.

Research Methodology

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.

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.

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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.

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.

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.

Data Presentation Format

Temperature gradient measurements from the 22 wells logged are summarized in Table 3-2. Detailed temperature-depth data are tabulated and plotted in Appendices A and B, respectively. Although data from all wells logged are given in Table 3-2 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 3-12 through 3-14.

Figure 3-12 shows selected temperature gradient data in New Mexico. Figure 3-13 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 3-12 and 3-13 are shown in Figure 3-14.

Figure 3-15 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 3-2. 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 3-12. 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 3-13. Average geothermal gradients in New Mexico.

CONTOURED NEW MEXICO GEOTHERMAL GRADIENTS

CONTOUR INTERVAL 10 °C/km

Figure 3-14. Geothermal gradient contours in New Mexico.

GENERALIZED GEOLOGIC MAP OF NEW MEXICO

Figure 3-15. 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 3-14 and 3-15).

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 3-16). 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, BERNALLILO 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 3-16. 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 3-16). 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 3-17 is an overlay for Figure 3-16 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

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 3-2 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 3-2) 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,

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 3-17. Location of geothermal exploration activities in the Santa Ana Pueblo area.

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.

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

Well Name: SAP/JD2

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°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

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)
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

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)
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

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)
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

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)
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

<u>Depth</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°C/km)</u>
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</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°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</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°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

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)
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

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)
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</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°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</u> <u>(m)</u>	<u>Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>Gradient</u> <u>(°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

Depth (m)	Temperature (°C)	Temperature Gradient (°C/km)
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

OJO CAL #2

WELL OJO CAL #1

WELL TAOS USFS

WELL RED RIV #2

WELL RED RIV #1

Part 3

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

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.

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 3-3, Figures 3-18 through 3-21, and Appendix A). An additional nine boreholes (see Table 3-4, Figures 3-22 and 3-23, 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, Part 3 is Dr. Chandler A. Swanberg, Associate Professor of Physics and Earth Sciences, New Mexico State University.

Table 3-3. 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 3-18. Temperature-depth curves for the Cravens#1 and Eckberg#1 boreholes.

Figure 3-19. Temperature-depth curves for the Eckberg #2 and Craves-P boreholes.

Figure 3-20. Temperature-depth curves for the Cravens-K and Packey Well boreholes.

Figure 3-21. Temperature-depth curves for the Rim Well, Cravens#2, and S-R#1 boreholes.

Table 3-4. 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 3-22. Temperature-depth curves for the LANL#1, LANL#2, and LANL#9 boreholes.

Figure 3-23. 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 3-5 for the La Bajada constriction. There are no data available for the Embudo constriction.

Discussion

Embudo Constriction

The thermal data within and adjacent to the Embudo constriction are shown in Figure 3-24. 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.

Figure 3-24. Temperature gradients observed near the La Bajada and Embudo constrictions in northern New Mexico.

Table 3-5. 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.

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.

La Bajada Constriction

The thermal data within and adjacent to the La Bajada constriction are shown in Figure 3-24, and the geochemical data are summarized in Table 3-5. The temperature gradients typically fall in the 40 to 50 °C/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°C/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 3-24 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.

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</u> <u>(m)</u>	<u>Temperature</u> <u>(°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.

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

Part 4

Thermal Data for Springs and Wells*

This Chapter 3, Part 4 consists of thermal and dissolved silica content data for springs and shallow groundwater wells. The data (see Table 3-6) have been compiled from the USGS water quality file (WATSTORE) but have not been field checked and may contain errors. Figure 3-25 contains the data of Table 3-6, Shearer and Reiter (1978), and field measurements obtained as part of this study.

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 3, Part 4 was compiled by Dr. Chandler A. Swanberg, Associate Professor of Physics and Earth Sciences, New Mexico State University.

Table 3-6. 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 3-6 (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 3-6 (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 3-6 (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 3-6 (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 Martínez or Godo	S	-	38.0	60
Gijosa Grant Río Grande	S	-	17.0	30
Ojo Caliente Grant Iron	S	-	40.0	-
Rancho Del Río 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 3-6 (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 Río Grant	S	-	21.0	-
Caja Del Río 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 3-6 (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 3-6 (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 3-6 (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 3-6 (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 3-6 (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 3-6 (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 3-6 (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 3-6 (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.

SUMMARY OF TEMPERATURE DATA - NORTHERN NEW MEXICO

Figure 3-25. Temperature data for springs and wells in north central New Mexico.

Part 5

Geothermal Resources of the Rio Grande Rift*

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).

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 3-26).

The Valles Caldera is located where the Rio Grande Rift intersects the Jemez Lineament (see Figure 3-26), 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 3-26 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 3-26. 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 3-26) should be considered as part of the Rio Grande Rift, has been adopted.

Figure 3-26. Distribution of groundwater barriers and constrictions within the New Mexico portion of the Rio Grande Rift.

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 3-27. 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 3-26 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 3-26. 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 3-26, 14 are associated with geothermal activity, and exceptionally high heat flow has been reported near two others (see Table 3-7). The remaining constriction (San Agustin) has been related to the Hot Springs in the Gila National

Figure 3-27. Qualitative forced convection basin model [after Morgan and Daggett (1981)].

Table 3-7. 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 Agustín	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 3-26). 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 3-26). 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 3-27). 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 3-26. 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.

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 3-26). 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 3-28 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 3-28). 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 3-28 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 3-29 shows a temperature gradient profile across the portion of the caldera which contains most of the deep geothermal wells. Figures 3-28 and 3-29 clearly demonstrate the high temperature nature of this geothermal area. The average geothermal gradient of the 70

Figure 3-29. Temperature gradient profile across the Valles Caldera. The section AA' is shown in Figure 3-28.

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 3-30. 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 3-31 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 3-28, 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 3-31 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.

Conclusions

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

Figure 3-30. Temperature-depth plots for selected geothermal wells in the Valles Caldera. The data have been taken from Rice (1981).

Figure 3-31. 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 3-26), as well as for the New Mexico portion of the Basin and Range Province (Morgan et al., 1983).

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Part 6

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

This Chapter 3, Part 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 3-8. Figure 3-32 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 3-8 and Figure 3-32 are included as part of the geothermal resources of New Mexico scientific map series (see Chapter 1).

References

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* The material contained in Chapter 3, Part 6 was compiled by Dr. Chandler A. Swanberg, Associate Professor of Physics and Earth Sciences, New Mexico State University.

Table 3-8. 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 3-8. (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 3-32. Groundwater chemistry for the Valles Caldera. The numbers refer to the sample numbers given in Table 3-8.

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Part 7

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

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.

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 3, Part 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)

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°C) 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 3-9. The data set contains both thermal and nonthermal waters from four different tectonic settings representing very diverse geologic settings.

Discussion of Results

Table 3-10 presents the basic geochemical information and Table 3-11 presents the statistical regression coefficients. Figures 3-33 through 3-37 show plots of geotemperature versus in-situ temperature for the SiO_2 (chalcedony), Na-K-Ca, K-Li, and Na-Li geothermometers, respectively.

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 3-9. 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 3-10. Summary of geothermometry data. The chemical data have been taken from Swanberg (1980).

Field Number	Name	Actual Temperature (°C)	Geotemperature (°C)								SiO2 (quartz)	SiO2 (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 3-10. (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			
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 3-10. (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 3-10. (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			
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 3-10. (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)
Tl1	Windmill	-	17	34	5	114	134	-	54.9	95.4	63
Tl2	Well	-	50	73	39	147	139	-	71.6	56.4	22
Tl3	Windmill	-	56	81	45	141	118	-	137.3	-6.6	-41
Tl4	-	-	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 3-11. Regression coefficients for various geothermometers against in-situ spring and well temperature. 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 3-33. SiO_2 (chalcedony) geotemperature vs. in-situ temperature.

Figure 3-34. Na-K-Ca geotemperature vs. in-situ temperature.

Figure 3-35. Na-K-Ca ($\beta = 4/3$) geotemperature vs. in-situ temperature.

Figure 3-36. K-Li geotemperature vs. in-situ temperature.

Figure 3-37. Na-Li geotemperature vs. in-situ temperature.

encountered in a geothermal system (see Table 3-10). 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 3-11 and Figure 3-33).. 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.

SiO₂ (Quartz) Geothermometer

The SiO₂ (quartz) geothermometer is based upon the same data as the SiO₂ (chalcedony) geothermometer, and, therefore, the regression coefficients are similar (see Table 3-11). The only difference between the two correlations is a slightly lower slope and a higher intercept for the SiO₂ (quartz) geothermometer, both of which result from a greater degree of quartz disequilibrium at lower temperatures.

Na-K-Ca Geothermometer

Tables 3-10 and 3-11 and Figure 3-34 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 3-35). The Na-K-Ca geothermometer, along with the SiO₂ 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.

Na-K Geothermometer

The geotemperatures calculated using the three Na-K geothermometers

(see Table 3-10) and the regression of the geotemperatures against in-situ temperature (see Table 3-11) 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.

K-Li Geothermometer

The K-Li geotemperatures are plotted against in-situ temperature in Figure 3-36 and the regression coefficients are given in Table 3-11. 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.

Na-Li Geothermometer

The Na-Li geothermometer (see Figure 3-37) has not been used in the geothermal evaluation for the same reasons as discussed for the K-Li geothermometer.

Conclusions

Nine geothermometers (see Table 3-10) 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.

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Chapter 4

Aeromagnetic and Bouguer Gravity Maps of New Mexico

Part 1

Composite Residual Total Intensity Aeromagnetic Map*

Introduction

An aeromagnetic anomaly map shows geology-related local variation in the magnetic field of the Earth. Total intensity means that the magnetometer is aligned in the Earth's field direction and, therefore, the magnitude of the the field but not its vector properties, is measured. Residual total intensity means that an approximation of the time-varying core and external-field components of the main geomagnetic field has been subtracted from the data. Composite map means that many individual maps have been patch-worked together. Overall, these modifying adjectives reflect an attempt to isolate the magnetic field that would be associated with the upper 10 to 20 kilometers of the crust of the Earth (i.e., above the Curie-point geotherm) if the crust was immersed in a uniform, stationary, inducing field in free space. By making these corrections, individual magnetic surveys in New Mexico obtained over a range of 5° of latitude and a period of nearly 40 years may be combined.

* The principal author of Chapter 4, Part 1 is Dr. Lindrith Cordell, U.S. Geological Survey.

Essentially all of the contour patterns on the map can be ascribed to magnetite. In general, other magnetic minerals are not volumetrically significant at the scale of the New Mexico map. With certain restrictions, the magnetic-intensity contours can be interpreted to reflect relative concentrations of magnetite, just as gravity contours can be interpreted to reflect relative concentrations of mass. The restrictions are: (1) magnetization depends on magnetic-domain size in addition to magnetite content; (2) remanent-magnetic anomalies may be important locally, and, in the case of reversed remanent magnetization, may appear as lows over highly magnetic sources; and (3) because of the inclined polarization of the Earth's inducing field, magnetic anomalies tend to occur somewhat to the south of the source, with a corresponding smaller-amplitude anomaly of opposite sign occurring on the north side of the source.

For practical purposes, in light of the scale of the New Mexico map, sedimentary rocks can generally be considered to be non-magnetic, with the only significant magnetic sources occurring in igneous and metamorphic terranes. The fact that thick sedimentary cover is effectively transparent magnetically is a major asset of the aeromagnetic data. This condition enables viewing through the sedimentary rock cover to detect intrusive igneous rocks or trends related to structural grain in the Precambrian crystalline basement. Unfortunately, effects of deep Precambrian structure are sometimes obscure in regions of shallow and generally highly magnetic volcanic fields.

All of the individual aeromagnetic surveys by the U.S. Geological Survey (USGS) in New Mexico have been published as large-scale maps, in

which presumably most of the economically-interesting buried plutons have already been identified. The synoptic view provided by the present 1:500,000 scale compilation may aid, however, in the study of the more regional features of the Precambrian basement and magmatic rocks of Tertiary and Quaternary age. In many parts of the state, the magnetic data represent virtually the only data available on the buried Precambrian terrane, and, thus, these are the data against which ideas of regional transcurrent faulting, fundamental zones of weakness, and the like, might be tested.

The present state map is accompanied by a digital data tape.* For purposes of detailed studies and construction of derivative maps, one should be able to extract from the digital data tape subsets of the data having reasonable fidelity to the original data at the original compilation scale.

Data Sets

During the period 1947 to the present, the USGS has flown or contracted for more than 30 large aeromagnetic projects covering, in all, about one-half of the area of New Mexico (see Figure 4-1). Actually, a slightly different number and designation of the projects is indicated on the USGS Aeromagnetic Map Index of New Mexico. Certain projects having similar survey specifications have been lumped together and others have been eliminated. Until recently, such aeromagnetic projects were not considered as elements of a systematic program to survey the entire state. Rather, these projects were obtained in

* This data tape is available from the National Oceanic and Atmospheric Administration (NOAA), Office of Geophysical Surveys, Boulder, CO 80302.

- NOTE: All NURE surveys flown 400 feet above terrain, and indicated by flight-line spacing only.**

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support of diverse, ad-hoc mineral resource assessments, national defense, and research studies, financed by a variety of state, federal, and tribal cooperatives, using widely variable survey design specifications. These USGS projects* were generally flown along one-mile spaced flight lines (see Figure 4-1). Since the mid-1970s, these surveys were flown under uniform design specifications (Godson, 1983), and all the original flight-line data (e.g., time-space coordinates, barometric and radar altimeter records, and total and residual magnetic fields) are available on magnetic tape. For earlier surveys, recovery of the data becomes increasingly problematical, and, in many cases, the best means of converting the data to digital form was simply to digitize the original published contour maps.

Reconnaissance-quality data for the approximately 40 percent of the state not covered by the more detailed USGS surveys were obtained from 3 and 6 mile-spaced surveys by the U.S. Department of Energy, National Uranium Resources Evaluation (NURE) program.** These surveys were all flown in the late-1970s at 400 feet above the ground, as required for the radiation measurements for which the surveys were primarily designed. There are some problems with the NURE data related to the widely-spaced flight lines, field gradients associated with rapid change in flight elevation, and the fact that the surveys were not suspended during magnetic storms.

* The USGS projects described in the New Mexico State Aeromagnetic Map Index are available from the U.S. Geological Survey, Office of Scientific Publications. Additional details about individual projects are (in most cases) available from the Chief, Branch of Geophysics, U.S. Geological Survey, Denver, CO 80225.

** Data tapes and detailed descriptions of the NURE data used for the New Mexico map are available from Bendix Field Engineering Corporation, Box 1569, Grand Junction, CO 81502.

No data were available for two small areas in southern New Mexico (see Figure 4-1) at the time the state map was prepared. The NURE data have very recently become available for the strip south of 32°N latitude. Coverage of the boomerang-shaped area of no data (i.e., the White Sands Missile Range area) is now being planned by the U.S. Geological Survey. These data and other new or improved data will be incorporated into the data tape as the data become available.

Composite Data Set

The preparation of a digital-data-based composite map actually results in two products: (1) the magnetic anomaly map, and (2) the digital data on magnetic tape. These two versions of the data differ significantly and will be discussed separately. At the root of the difference is the fact that adjacent magnetic surveys flown at two different levels cannot be joined together without degrading part of the data.

In preparing the New Mexico map, the philosophy that the digital data tape should preserve the original data everywhere was followed, whereas discontinuities at project boundaries were smoothed in the map to facilitate interpretation of the map by inspection.

Digital Data

The basic data grid is in units of decimal degrees with a grid interval of 0.005 degrees (18 seconds) of latitude and longitude. The grid interval in the east-west direction varies from 472 meters on the south to 445 meters on the north. The grid interval in the north-south direction is 555 meters. Only a single residual magnetic field value is associated with each grid point. In cases of data overlap, the better data were used.

Flight elevation information is not included within the digital data set. The data were not analytically continued onto a common level, nor were surveys which were flown at constant terrain clearance (i.e., draped surveys) projected onto a local level surface. Most of the USGS surveys were flown at a constant elevation, and the elevation of each survey is indicated in Figure 4-1. Design-specified terrain clearance of draped USGS surveys is also indicated in Figure 4-1. These surveys were flown by fixed-wing aircraft. Thus, the actual terrain clearance is a smoothed version of the topography, plus the intended clearance. All the NURE surveys were flown draped at 400 feet terrain clearance, using both fixed-wing aircraft and helicopters.

The primary observational data consist of discrete measurements of the Earth's field at a point defined by latitude, longitude, elevation, and time. These measurements are distributed along flight lines in the case of data obtained directly from the original survey tapes, or along flight lines, plus additional random points, in the case of data reconstructed by digitization of published contour maps. For each survey, these irregularly-spaced data were interpolated onto the basic 0.005-degree grid by means of a computer program (Webring, 1982) based on minimum curvature (Briggs, 1974). In the case of draped data, this step, which is standard practice, entails an implicit assumption that the surface of observation has also somehow been interpolated.

In principle, the geomagnetic reference field appropriate for the date and location of a given survey is subtracted from the total-intensity grid to yield the residual total-intensity grid. This step is complicated by several problems. The International Geomagnetic Reference Field (IGRF) has been revised through the years. A Definitive

Geomagnetic Reference Field (DGRF) for 1965 to 1975 and a Provisional Geomagnetic Reference Field (PGRF) for 1975 to 1980 have been adopted by the International Association of Geomagnetism and Aeronomy (Peddie, 1982a; Peddie, 1982b). The PGRF may be revised in the future. For the New Mexico magnetic anomaly map and associated digital data set, all surveys flown between 1965 and the present were reduced (or in certain cases were re-reduced) using the DGRF, the PGRF, or IGRF #80. Data flown in the period 1955 to 1965 were reduced using IGRF 1965. Data flown prior to 1955 were reduced by means of the Goddard Space Flight Center reference field GSFC 12/66 (Cain et al., 1967).

To complicate the treatment of the problem of removal of the time-varying geomagnetic reference field even further, in some of the early surveys the total-intensity field was referenced to an arbitrary (and by now forgotten) datum. In these cases, the absolute datum level had to be determined approximately by matching with adjacent surveys. In no case was an arbitrary tilt applied to a survey in order to improve the match.

In summary, each survey was digitized, gridded, level-shifted where necessary, and converted to a uniform DGRF or related residual. The digital data set, therefore, simply consists of all the individual reduced-to-residual grids joined together into a master grid, with a grid interval of 0.005 degrees, defined from -107 to -102° longitude (1,201 columns) and 31.33 to 37° latitude (1,135 rows). A single residual total-intensity value is associated with each grid point and these data are available on magnetic tape. Survey elevation is indicated in Figure 4-1, and, in some cases, is described in greater detail in the original survey records.

Composite Map

The New Mexico data, comprised of surveys flown over a period of 36 years and an elevation range of 3,000 to 13,500 feet above sea level, present severely adverse conditions in compiling a composite aeromagnetic map from digital data. It is intuitively apparent because of the attenuation of potential fields with distance from the source that, if aeromagnetic surveys flown at different elevations are joined together, a discontinuity will occur at the boundary. As a consequence of potential-field theory, aeromagnetic data observed on one level can be calculated on another level by analytical continuation (Henderson, 1970). In practice, downward continuation to a common level is unstable and essentially unworkable for the purpose here; upward continuation to a common level severely smooths the data and actually distorts the data in a fairly wide region in the vicinity of survey boundaries.

Three different techniques for treating the variable-elevation problem were tried as follows:

- 1) Continuation to a common flight level. This technique is the most satisfying mathematically and was used by Sweeney et al. (1978) in making a composite aeromagnetic map of Nevada. In practice, this approach requires upward-continuation to the level of the highest survey. Continuation to 13,500 feet resulted in severe attenuation and loss of information in eastern and especially southeastern New Mexico.
- 2) Continuation onto an irregular surface a constant distance above the Precambrian basement. This method could likely become the optimal solution to the problem but, at present, the method is limited by problems with downward continuation. Using frequency-domain filters modified from Cordell and Grauch (1982) and other new methods, extreme downward continuation has been effected. Even so, continuation of the New Mexico data onto a surface a constant distance above the basement required upward continuation of the data in areas where the basement was structurally high. The draped-above-basement map was an improvement over the constant (13,500 feet) elevation map, but, in this case, upward continuation caused attenuation of signal over shallow basement, whereas downward-continuation introduced some noise over deep basement.

- 3) Simply join adjacent surveys together and smooth the discontinuity at the border by means of spline functions. This method has been used by Anderson (1971) and in unpublished USGS computer programs (Sweeny and Webring, 1983).

Because the third method resulted in the least attenuation and smoothing of the data, this method was used for the New Mexico map. Normally, only data in a 2-kilometer-wide strip at the project boundaries were modified; locally, a wider zone was needed to obtain a smooth join. Especially glaring survey boundaries will be seen. The intent was not to deny the existence of mathematically inevitable discontinuities at project boundaries, but rather to subdue those linear features sufficiently so that the eye would not be drawn away from geological trends.

The modified composite grid was projected to the Lambert conformal projection of the New Mexico state base map, regridded to a 1-kilometer grid, and contoured, using various USGS computer programs. Although the map was primarily computer-generated, a few cosmetic changes were added by hand. Figures 4-2 and 4-3 are composite residual total intensity aeromagnetic maps of New Mexico originally drafted at a scale of 1:500,000.

Even though some of these data have been available for many years, there is much new information to be obtained from the synoptic view of the magnetic anomalies shown on the map (see Figures 4-2 and 4-3). This condition is especially true when the aeromagnetic map is overlain on the New Mexico geologic map (Dane and Bachman, 1965). Still more information is available by comparing the gravity and the aeromagnetic maps, and in viewing the geophysical maps in color.

On the other hand, the aeromagnetic map at this stage is a collage of whatever data are available and should be regarded as preliminary.

Figure 4-2. Composite residual total intensity aeromagnetic map of northern New Mexico. The data are given in 50-nanotesla (gamma) contours using an arbitrary zero.

Figure 4-3. Composite residual total intensity aeromagnetic map of southern New Mexico. The data are given in 50-nanotesla (gamma) contours using an arbitrary zero.

Much of the coverage provided by the NURE data and some of the older data is inadequate. The digital data set can be easily updated and, perhaps, the composite aeromagnetic map will stimulate opportunities to do so.

Acknowledgments

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Part 2

Bouguer Gravity Map of New Mexico*

This Chapter 4, Part 2 consists of the complete Bouguer gravity map of New Mexico, which will be included as part of the scientific geothermal resources map of New Mexico (Swanberg, 1983). Figures 4-4 and 4-5 are complete Bouguer gravity maps of New Mexico originally drafted at a scale of 1:500,000.

The following criteria and comments relate to Figures 4-4 and 4-5.

1. Reduction density is 2.67 g/cm^3 .
2. Terrain correction for the region extending radially from 1 to 167 kilometers from each gravity station was made by the computer method of Plouff (1977).
3. Terrain correction was not made in the zone 0 to 1 kilometers from each station, nor beyond 167 kilometers, except that the terrain correction includes a correction for the curvature of the Earth.
4. Observed gravity is referenced to the IGSN-71 gravity base network (Morelli et al., 1974).
5. Theoretical gravity was calculated according to the 1967 reference figure (International Association of Geodesy, 1967).
6. The data base and reduction procedures are described in greater detail by Cordell, Keller, and Hildenbrand (1982).
7. An updated data tape is available from G.R. Keller.

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Figure 4-4. Complete Bouguer gravity map of northern New Mexico. The data are given in 10-mgal contours.

Figure 4-5. Complete Bouguer gravity map of southern New Mexico. The data are given in 10-mgal contours.

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Chapter 5

A Summary of the Low Temperature Geothermal Resource Assessment Program in New Mexico*

Introduction

The New Mexico State University Energy Institute (NMSUEI) has managed the four-year research effort on low-temperature geothermal resource exploration and assessment that has been supported by the Department of Energy State-Coupled Low Temperature Geothermal Resource Assessment Program. This broadly based research, performed principally by faculty and staff at the University of New Mexico, the New Mexico Institute of Mining and Technology, and New Mexico State University has revealed numerous areas in New Mexico that may contain commercially exploitable low-temperature geothermal resources. At present, the knowledge about each area varies: some areas require additional reconnaissance-level investigations, and others warrant detailed local surveys, including temperature gradient drilling for reservoir confirmation. An important component of this program has been basic studies in specific regions of New Mexico, including areas adjacent to the cities of Albuquerque, Las Cruces, Socorro, and Truth or Consequences. Considerable geological, hydrological, electrical resistivity, gravity, magnetic, seismic, water analysis, and subsurface temperature data have been compiled and analyzed by university researchers for these locations.

* The author of Chapter 5 is Dr. Larry Icerman, Director, New Mexico State University Energy Institute.

Specific State-Coupled Program Accomplishments

During the four-year research program, a total of 25 tasks have been undertaken (Icerman, Starkey, and Trentman 1980; Icerman, Starkey, and Trentman, 1981; and Icerman and Starkey, 1982). Eleven of these tasks were focused toward collecting and compiling statewide data, six were regional studies covering more than one county, and eight were research projects directed primarily toward data collection near specific cities or known resource areas. Two of these latter studies contributed significantly to the confirmation of the Las Alturas geothermal anomaly east of Las Cruces, which has now been expanded nearly 50-fold as the result of temperature gradient drilling funded jointly by the State of New Mexico and private industry (Lohse and Icerman, 1982). The following three subsections give a brief summary of the program accomplishments by task. A detailed bibliography for low temperature geothermal resource assessment in New Mexico based on work supported by the State-Coupled Program has been published previously (Icerman, 1982).

Statewide Studies and Results

1. Compilation of spring and well temperatures in excess of 20°C
 - * Nearly all groundwaters in southern New Mexico have temperatures in excess of 20°C
 - * Numerous geothermal prospects in western New Mexico contain high-quality, high-temperature waters suitable for direct-use applications
 - * At least seven and perhaps as many as 20 areas may have subsurface temperatures in excess of 150°C, which is suitable for electricity production
2. Analysis and mapping of existing deep oil, gas, and water well data
 - * Bottom-hole temperatures in deep wells in seven New Mexico counties compiled and mapped

- * 46 anomalous low-temperature geothermal areas in New Mexico identified

3. Collection of oil and gas well data

- * 15,732 data points collected throughout New Mexico, most wells in Rio Arriba (4,625) and San Juan (7,850) counties
- * Average San Juan Basin oil and gas well temperature gradient is $26.9^{\circ}\text{C}/\text{km}$
- * Bottom-hole temperature depth plot completed for north-western counties
- * 149 wells identified with temperature gradients of $40^{\circ}/\text{km}$ or higher

4. Tabulation of water quality information

- * Most thermal waters in New Mexico have salinities in the range of 1,000 to 3,000 ppm total dissolved solids
- * Several areas in the Gila National Forest and near Socorro have salinities below 400 ppm total dissolved solids
- * Only known geothermal area in New Mexico associated with high levels of objectionable chemical constituents is the Valles Caldera region

5. Compilation of heat flow data

- * Zone of high heat flow (> 2.5 HFU) trends north to south through central New Mexico and is associated with the Rio Grande Rift
- * Heat flow values in the Basin and Range fall between 2 and 3 HFU
- * Colorado Plateau and eastern New Mexico have nearly normal heat flow values of about 1.5 HFU

6. Collection of seismicity data

- * 53 earthquakes with modified Mercalli of 5 or greater reported prior to 1961, approximately 67% located in the Rio Grande Rift
- * 224 earthquakes recorded during the period 1961 through 1977, with local magnitudes greater than 1.5
- * 23 earthquakes with local magnitudes ($M_L > 1.5$) occurred from 1978 through 1980, principally within the Rio Grande Rift
- * Highest amount of activity was in the central part of the rift near Socorro

7. Collection and mapping of Quaternary volcanism and tectonism information

- * Locations of Quaternary and late-Pliocene tectonic activity and volcanism mapped
 - * Quaternary and late-Pliocene age dates, mining prospects, and water isotope analyses mapped
8. Construction of a lineament map of New Mexico (scale, 1:500,000)
 - * Fault system is dominated by NW and NE orthogonal set of faults
 - * N-S faults are restricted to the Rio Grande Rift, west and southwest of New Mexico
 - * Basin and Range is dominated by NW faults
 - * Most known geothermal areas lie at intersections of the Rio Grande Rift and NW-SE transform zones
 9. Compilation of data resulting from geoelectric investigations supplemented with field study data
 - * Index map for geoelectrical studies in New Mexico
 - * 147 geoelectrical study references compiled
 10. Completion of the public and scientific geothermal resources maps of New Mexico (scale, 1:500,000)
 - * Public geothermal resources map published in 1980
 - * Scientific geothermal resources map to be published in 1983 (see Chapter 1)
 11. Preparation of an aeromagnetic map of New Mexico (see Chapter 4)

Regional Studies and Results

1. Updated temperature data from existing water wells in southwestern New Mexico
 - * 98 water wells identified, 13 suitable for temperature logging
 - * Most boreholes were shallow (<25m) and cold
 - * 3 wells identified as anomalous, two in known areas of geothermal promise
2. Interpretation of geological, geophysical, and hydrologic data to assess geothermal energy potential in Catron, Dona Ana, Grant, Hidalgo, Luna, and Sierra counties
 - * Hydrothermal systems associated with late-Quaternary faulting
 - * Known geothermal areas coincide with intersections of NW-SE and N-S trends of structural weakness

- * Maps (scale, 1:250,000) of tectonic features, gravity, temperature data geothermal anomalies completed
 - * 4 temperature gradient holes drilled with above normal heat flow values of 2.5 to 3.5 HFU
3. Fault mapping and age dating in the Columbus, Black Range, Potrillo Mountain, and southern Tularosa Basin areas
 - * Locations of all known faults in south central New Mexico which have been active during the last 0.4 million years mapped
 - * 15 basaltic volcanic rocks determined by radiometric dating
 - * 14 basaltic volcanic rocks classified by chemical analyses and mineralogical studies
 4. Electrical resistivity studies in Dona Ana and Luna counties
 - * Schlumberger depth soundings along three Schlumberger profiles completed
 - * Faults interpreted from resistivity profiles plotted for the Las Cruces area
 5. Interpretation of geological and geophysical data to assess geothermal energy potential in Bernalillo, Los Alamos, Mora, Rio Arriba, San Miguel, Sandoval, Santa Fe, Taos, Torrance, and Valencia counties (see Chapter 3)
 6. Geothermal exploration in Otero and Lincoln counties (see Chapter 2)

Area-Based Studies and Results

1. Seismic, water analyses, and hydrology studies in the Socorro area
 - * Tritium activity, major chemical constituents, deuterium, and oxygen-18 concentrations determined in selected samples of springs, wells, groundwaters, and precipitation
 - * Depth to the aquitard in the Upper Popotosa Formation determined (at depths greater than 2,200 m) by active seismic reflection techniques
2. Mapping of hot springs and faults, gravity and aquifer studies, and temperature logging of existing wells in the Truth or Consequences area
 - * Geological mapping of the Mud Springs Mountains area
 - * Thermal and nonthermal aquifers identified and described by geological mapping, field observations, aerial photography, and direct measurements

- * Discharge area geology and age of fault-controlled springs described
 - * 6 water wells temperature logged
3. Magnetic and electrical resistivity surveys and drilling temperature gradient holes on the Albuquerque west mesa
 - * Ground magnetic surveys (175 km²) completed
 - * Two dipole-dipole lines (5 and 8 km) completed
 - * 5 deep (280 to 440 m) water wells logged
 - * Highest measured temperature gradient in over 100 holes is 120°C/km
 4. Computer-based hydrologic study of the Animas Valley/Lightning Dock KGRA area
 - * Hydrogeologic data collected, reviewed, and analyzed statistically
 - * Flow net analysis performed
 - * Calibrated two-dimensional computer model developed to predict drawdown, water level, and hydraulic head
 - * Maps of groundwater temperature, salinity, and chloride, sulfate, sodium, and lithium concentrations prepared
 5. Temperature and heat flow investigations in Dona Ana County
 - * 62 abandoned water wells and shallow temperature gradient holes temperature logged
 - * Conductive heat flow values about the water table have a modal class of 2.4 to 3.6 HFU and a range exceeding -1 to 16 HFU
 - * Cool groundwater recharge and lateral groundwater flow and upward convecting hot water are believed to be the cause of the anomalously low and high heat flow values, respectively
 - * Geological, geophysical, and hydrologic data suggest the existence of a fault-controlled hydrothermal system
 6. Electrical resistivity studies in the Chamberino and Mesquite areas
 - * Zone of low resistivity (10 km long by 5 km wide) identified by Schlumberger soundings and profiles
 - * Electrical resistivity data suggest complex faulting and upwelling of geothermal fluids along faults
 7. Seismic profiles of the Las Alturas geothermal reservoir
 - * Gravity, magnetic, seismic-refraction, and seismic-reflection data sets collected and compared

- * Seismic reflection data indicate that there is no major faulting above 1,000 ft
- * Rise of geothermal waters near test holes is predicted to be pore- or microfracture-controlled, rather than major fracture-controlled, flow

8. Drilling of two 1,000-foot exploratory geothermal wells

- * 8 water wells in the Las Alturas area temperature logged
- * 6 30-m temperature gradient wells drilled
- * 300-m and 360-m slim gradient holes drilled with bottom-hole temperatures of 145°F and 123°F, respectively

Geothermal Maps of New Mexico

During 1980, a major step toward the initial goals of the low-temperature geothermal resource assessment program was taken when the Geothermal Resources of New Mexico map was published (Swanberg, 1980). This map, designed for use by the general public, entrepreneurs, and regional planners, shows data on thermal springs and wells (e.g., temperatures, flow rates, salinities, and depths), heat-flow values, delineated low-temperature resource areas, and descriptions of present or projected geothermal energy users. Land status, including Known Geothermal Resource Areas, and topographic data are also displayed on this map.

A scientific geothermal resources map, showing basic geological, geochemical, and geophysical data, will be published following the completion of the program in 1983 (see Chapter 1). This map, the first state scientific geothermal map to be printed by the National Oceanic and Atmospheric Administration, will include selected technical references so that interested individuals may access data for specific sites. The base map will display late-Tertiary and Quaternary volcanic and

tectonic features, late-Tertiary and Quaternary igneous age dates, hot springs and wells, and heat flow values. Earthquake epicenters, heat-flow contours, and seismic risk contours, anomalous oil and gas well data, and data from the Valles Caldera will be shown as insets. Three overlays (hydrology-geochemistry, Bouguer gravity, and aeromagnetic data) will be included as part of the map series. Deep sedimentary basins, groundwater constrictions, and temperature gradient contours based on oil and gas well data will be shown on the hydrology-geochemistry overlay. This overlay will also contain geochemical anomalies, stiff diagrams for most geothermal waters, as well as available oxygen and hydrogen isotope data, and temperatures estimated by the SiO_2 and Na-K-Ca geothermometers.

State of New Mexico Activities

During the period from 1974 through 1982, the State of New Mexico funded 49 geothermal energy research and development projects for a total expenditure of more than \$2 million (New Mexico Energy Research and Development Institute, 1982). These projects covered a wide range of activities from surface exploration, system feasibility studies, engineering design, commercialization programs, to test well drilling. Some of these projects were direct New Mexico contributions to the federally-funded State-Coupled Low Temperature Geothermal Resource Assessment Program. Approximately \$1.2 million have been committed to 26 projects that are either directly-linked or closely related to the goals of the State-Coupled Program, which has had cumulative expenditures of about \$0.9 million. Much of the data collected by these state-funded research programs is summarized on the Geothermal Resources

of New Mexico public map or will be included in the scientific map series.

Program Success

The resource assessment programs in New Mexico have been very successful in: (1) delineating low-temperature geothermal resources throughout New Mexico on statewide, regional, and area-specific scales; (2) developing a strong community of in-state geothermal energy research and development professionals and practitioners; and (3) elevating the level of awareness of geothermal energy potential among commerce, industry, and the general public. The ultimate measure of success of a resource assessment and exploration program must be the identification of commercially-viable geothermal resources. Reservoir confirmation, based on site-specific surface studies followed by test and production drilling, is a key and necessary element in the development of commercial applications of low-temperature geothermal energy resources. In New Mexico, experience indicates that neither private resource developers nor potential users will take the financial risks necessary to gain sufficient knowledge of low-temperature resources to make commercial developments a reality, without considerable expenditure of public funds to reduce the risks of drilling the first production well in any resource area.

An excellent example of the use of public monies to build this knowledge base is the geothermal heating project at the New Mexico State University campus. Support from the State-Coupled Low Temperature Geothermal Resource Assessment Program allowed a resource with no surface manifestations to be identified, temperature gradient holes to

be drilled, and the first production well to be completed, which permitted additional State and Department of Energy funds to be obtained to perform a system design and complete a second production well. This work provided the necessary background information for use in acquiring additional funds from the State of New Mexico to construct a low-temperature ($\sim 140^{\circ}\text{F}$) geothermal energy system that delivers approximately 10 million Btu per hour to heat domestic hot water for 30 campus buildings (including five multi-structure dormitories), for space heating of the natatorium and football stadium complex, and for heating the indoor and outdoor swimming pools. Dedication of the \$1.2 million project occurred in April 1982. This project, which will save New Mexico taxpayers in excess of \$300,000 per year on natural gas purchases at 1982 prices, would not have become a reality without the initial support from the State of New Mexico and the State-Coupled Low Temperature Geothermal Resource Assessment Program.

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