DOE/ID/01717--3

DE82 014292

DOE/ID 1717-3

Distribution Category UC-66b

STATE-COUPLED LOW TEMPERATURE GEOTHERMAL
RESOURCE ASSESSMENT PROGRAM,
FISCAL YEAR 1981

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

FINAL TECHNICAL REPORT

Edited by

950 5791 Larry Icerman and Arlene Starkey
New Mexico Energy Institute
at
New Mexico State University
Las Cruces, New Mexico 88003

Larry Icerman
Principal Investigator

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE.
It has been reproduced from the best available
copy to permit the broadest possible availability.

January 1982

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

MBW

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared to document work sponsored by the United States government. Neither the United States nor its agent, the United States Department of Energy, nor any federal employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

FOREWORD

This report summarizes the results of low-temperature geothermal energy resource assessment efforts in New Mexico during the period from May 15, 1980, through June 14, 1981, under the sponsorship of the U.S. Department of Energy (Contract DE-AS07-78ID01717). The research program was administered by the New Mexico Energy Institute at New Mexico State University and the research was conducted by private consultants and by university faculty and staff members at New Mexico State University, the New Mexico Institute of Mining and Technology, the University of New Mexico, Michigan Technological University, and San Diego State University.

The report is divided into eight chapters, which correspond to the tasks delineated in the above contract. This work extends the knowledge of low-temperature geothermal reservoirs in New Mexico with the potential for direct heating applications. 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 and the National Oceanic and Atmospheric Administration for inclusion in the GEOTHERM data file and for preparation of New Mexico low-temperature geothermal resources maps. Funding from the United States Geological Survey, the National Science Foundation, and the State of New Mexico Energy and Minerals Department supported work from which some data compiled in this research effort were taken.

We acknowledge the special efforts of Nora Trentman, who assisted us in the early stages of the editing process, and Mona Ytuarte, who typed the final version of the complete manuscript.

L. Icerman

A. Starkey

TABLE OF CONTENTS

		<u>Page</u>
Chapter 1	Public and Technical Geothermal Resources of New Mexico Maps. <i>Chandler A. Swanberg</i>	1-1
Chapter 2	Locating Geothermal Anomalies Using Bottom-Hole Temperatures from Oil and Gas Wells in New Mexico. . . <i>Lokesh Chaturvedi</i>	2-1
Chapter 3	Updating of New Mexico Seismic Data. <i>Allan R. Sanford</i>	3-1
Chapter 4	Lineament Map of the State of New Mexico <i>Larry Lepley</i>	4-1
Chapter 5	Collection of Existing Water Well Data in the Southern Rio Grande Rift and Southwestern New Mexico <i>Richard L. Lohse</i>	5-1
Chapter 6	Temperature Gradient, Resistivity, and Magnetic Surveying on the West Mesa of Albuquerque. <i>George R. Jiracek</i>	6-1
Chapter 7	Resource Assessment in Southwestern New Mexico (Catron, Dona Ana, Grant, Hidalgo, Luna, and Sierra Counties).	7-1
Part 1	Electrical Resistivity Studies <i>Charles T. Young</i>	7-1
Part 2	Temperature Studies in Southwestern New Mexico . . . <i>Richard L. Lohse</i>	7-37
Chapter 8	Hydrologic Study of the Animas Valley-Lightning Dock KGRA Areas. <i>David B. Hawkins and Daniel B. Stephens</i>	8-1

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
2-1	Temperature vs. depth distribution for oil and gas wells located in the San Juan Basin.	2-5
2-2	Temperature vs. depth distribution for oil and gas wells located in the Permian Basin.	2-6
2-3	Temperature vs. depth distribution for oil and gas wells in New Mexico located in areas other than the San Juan and Permian basins.	2-7
2-4	Locations of oil and gas wells in New Mexico with computed anomalous geothermal gradients based on bottom-hole temperatures.	2-16
2-5	Artesian hot water (62°C) discharge from Gallo Wash No. 1 Well in the southeastern part of San Juan County.	2-18
2-6	Artesian hot water (65°C) discharge from Mesa Petroleum Company Well near Navajo Lake in the northeastern part of San Juan County.	2-19
3-1	Instrumental epicenters for earthquakes ($M_L > 1.5$) recorded during the period 1978 through 1980.	3-5
4-1	A lineament map of northern New Mexico.	4-7
4-2	A lineament map of southern New Mexico.	4-8
4-3	Plate configurations in western New Mexico during the Paleocene Epoch.	4-9
4-4	Plate configurations in western New Mexico during the Eocene Epoch.	4-10
4-5	Plate configurations in western New Mexico during the Miocene Epoch.	4-11
4-6	Plate configurations in western New Mexico during Pliocene-Quaternary time.	4-12
5-1	Locations of wells examined for temperature logging in Dona Ana County.	5-2
5-2	Locations of wells examined for temperature logging in Grant County.	5-4
5-3	Locations of wells examined for temperature logging in Hidalgo County.	5-6

<u>Figure</u>	<u>Page</u>
5-4 Locations of wells examined for temperature logging in Luna County.	5-8
5-5 Locations of wells examined for temperature logging in Sierra County.	5-10
5-6 Temperature-depth profiles for the wells logged with depths shallower than 70 meters.	5-16
5-7 Temperature-depth profiles for the wells logged with depths greater than 70 meters.	5-17
6-1 Base map of Llano de Atrisco area west of Albuquerque. . . .	6-2
6-2 Shallow temperature gradient map of Llano de Atrisco. . . .	6-6
6-3 Bipole-dipole total field apparent resistivity map of Llano de Atrisco obtained from VNS BD2 transmitter.	6-7
6-4 Dipole-dipole observed and calculated pseudosections and calculated resistivity model along Line 0 of Llano de Atrisco.	6-9
6-5 Dipole-dipole observed and calculated pseudosections and calculated resistivity model along Line 1.75 of Llano de Atrisco.	6-10
6-6 Total magnetic field map of Llano de Atrisco.	6-11
6-7 Magnetic prism model.	6-14
6-8 Calculated magnetic anomaly crossed on Line 4N of Llano de Atrisco.	6-16
6-9 Complete Bouguer gravity map of Llano de Atrisco.	6-17
6-10 Profiles of shallow thermal gradient, magnetic, gravity, and resistivity surveys on Llano de Atrisco.	6-19
6-11 Hypothetical Rio Grande Rift forced groundwater convection system and expected surface heat flow profile.	6-21
6A-1 Llano de Atrisco magnetic survey Line 8S.	6-27
6A-2 Llano de Atrisco magnetic survey Line 7S.	6-28
6A-3 Llano de Atrisco magnetic survey Line 6S.	6-29
6A-4 Llano de Atrisco magnetic survey Line 5S.	6-30
6A-5 Llano de Atrisco magnetic survey Line 4S.	6-31
6A-6 Llano de Atrisco magnetic survey Line 3S.	6-32

<u>Figure</u>		<u>Page</u>
6A-7	Llano de Atrisco magnetic survey Line 1S.	6-33
6A-8	Llano de Atrisco magnetic survey Line 0.	6-34
6A-9	Llano de Atrisco magnetic survey Line 1N.	6-35
6A-10	Llano de Atrisco magnetic survey Line 2N.	6-36
6A-11	Llano de Atrisco magnetic survey Line 3N.	6-37
6A-12	Llano de Atrisco magnetic survey Line 4N.	6-38
6A-13	Llano de Atrisco magnetic survey Line 5N.	6-39
6A-14	Llano de Atrisco magnetic survey Line 6N.	6-40
6A-15	Llano de Atrisco magnetic survey Line 7N.	6-41
6A-16	Llano de Atrisco magnetic survey Line 8N.	6-42
6A-17	Llano de Atrisco magnetic survey Line 9N.	6-43
6A-18	Llano de Atrisco magnetic survey Line 10N.	6-44
6A-19	Llano de Atrisco magnetic survey Line 11N.	6-45
6A-20	Llano de Atrisco magnetic survey Line 12N.	6-46
6A-21	Llano de Atrisco magnetic survey Line 13N.	6-47
7-1	Survey areas in Luna and Dona Ana counties.	7-4
7-2	Apparent resistivities near Columbus, New Mexico calculated from airborne electromagnetic measurements (Barringer Input System).	7-5
7-3	Survey line C-C' on the Dwyer 15-Minute Quadrangle in northern Luna County.	7-6
7-4	Profile C-C' from the Dwyer 15-Minute Quadrangle.	7-7
7-5	Survey lines A-A' and B-B' on the Nutt 15-Minute Quadrangle.	7-9
7-6	Profile A-A' from the Nutt 15-Minute Quadrangle.	7-10
7-7	Profile B-B' from the Nutt 15-Minute Quadrangle.	7-11
7-8	Contours of the lowest-apparent resistivity at each station.	7-13

<u>Figure</u>		<u>Page</u>
7-9	Contours of depth to electrical basement from the automatic computer interpretations.	7-15
7-10	Locations of profiles in Dona Ana County.	7-16
7-11	Cross-sectional structural interpretation of Profile O across Interstate 25 near Rincon, New Mexico.	7-18
7-12	Cross-sectional structural interpretation of Profile A across the northern outskirts of Las Cruces and extending out into the Jornada del Muerto.	7-19
7-13	Cross-sectional structural interpretation of Profile B extending westward from the western outskirts of Las Cruces.	7-20
7-14	Cross-sectional structural interpretation of Profile C east of Las Cruces, north of the Las Alturas geothermal field. .	7-21
7-15	Cross-sectional structural interpretation of Profile N lying along a north-south line east of Las Cruces. . . .	7-22
7-16	Cross-sectional structural interpretation of Profile M approximately parallel to Profile N on the east side of Tortugas Mountain.	7-23
7-17	Cross-sectional structural interpretation of Profile D about three miles south of Profile B and extending from the outskirts of Las Cruces into the desert near La Mesa. . . .	7-24
7-18	Cross-sectional structural interpretation of Profile E across the Rio Grande and Interstate Highway 10 about two miles north of the Black Mesa lava flow.	7-25
7-19	Cross-sectional structural interpretation of Profile I across the Mesilla Valley near San Miguel and Mesquite. . .	7-26
7-20	Cross-sectional structural interpretation of Profile R which extends from near Kilbourne Hole past Berino and into the low hills to the east.	7-27
7-21	Cross-sectional structural interpretation of Profile F west of Profile EE less than six miles from the international boundary between New Mexico and Mexico.	7-28
7-22	Cross-sectional structural interpretation of Profile EE east of Profile F less than six miles from the international boundary between New Mexico and Mexico.	7-29
7-23	Faults interpreted from resistivity profiles near Las Cruces.	7-34

<u>Figure</u>		<u>Page</u>
7-24	Location map of the area in southwestern New Mexico surveyed for geothermal potential.	7-38
7-25	Actual temperatures ($^{\circ}\text{C}$) of springs and of wells less than 150 m in southwestern New Mexico.	7-39
7-26	Locations of springs and of wells less than 150 m deep in southwestern New Mexico with actual temperatures between 30° and 40°C	7-41
7-27	Bottom-hole temperature gradients ($^{\circ}\text{C}/\text{km}$) of wells in southwestern New Mexico for an assumed surface temperature of 20°C	7-42
7-28	SiO_2 geotemperatures ($^{\circ}\text{C}$) of springs and wells in southwestern New Mexico.	7-58
7-29	Na-K-Ca geotemperatures ($^{\circ}\text{C}$) of springs and wells in southwestern New Mexico.	7-59
7-30	Na-K-Ca (Mg corrected) geotemperatures ($^{\circ}\text{C}$) of springs and wells in southwestern New Mexico.	7-60
7-31	Late Cenozoic faults, volcanic rocks and vents, and locations and ages of dated basaltic rocks.	7-62
7-32	Complete Bouguer gravity anomaly map of southwestern New Mexico.	7-64
7-33	Residual Bouguer gravity anomaly map of southwestern New Mexico.	7-65
7-34	Sites in southwestern New Mexico characterized by anomalous actual well and spring temperatures ($\geq 30^{\circ}\text{C}$), bottom-hole temperature gradients ($\geq 60^{\circ}\text{C}/\text{km}$) of wells, or by anomalous actual temperatures ($\geq 40^{\circ}\text{C}$) of thermal springs.	7-66
7-35	Sites in southwestern New Mexico characterized by anomalous SiO_2 , Na-K-Ca, and Na-K-Ca (Mg corrected) geotemperatures of springs and wells.	7-67
7-36	Sites in southwestern New Mexico characterized by anomalous geotemperatures, actual well temperatures, bottom-hole temperature gradients, and thermal spring temperatures. . .	7-69
7-37	Location map for temperature-gradient holes in the Deming-Faywood area.	7-72
7-38	Geophysical and geological data for the Deming-Faywood area.	7-73
7-39	Temperature-depth profiles of the four temperature-gradient holes in the Deming-Faywood area.	7-78

<u>Figure</u>		<u>Page</u>
8-1	General location map.	8-3
8-2	Lower Animas Valley-Lightning Dock KGRA study area.	8-4
8-3	Complete Bouguer gravity anomaly map.	8-10
8-4	Water-level (hydraulic head) contours predicted by the kriging technique (elevations in ft above mean sea level).	8-16
8-5	Distribution of standard deviations of error for the hydraulic head predicted by the kriging technique.	8-17
8-6	Natural logarithm of transmissivity predicted by the kriging technique.	8-18
8-7	Distribution of the kriging technique standard deviations of error for the natural logarithm of transmissivity predicted by the kriging technique.	8-19
8-8	Steady-state flow net.	8-25
8-9	Finite-difference mesh used in the computer simulation.	8-32
8-10	Simulated steady-state water-level elevations from computer model calibrations.	8-34
8-11	Annual irrigation pumpage.	8-37
8-12	Total water availability and consumptive use in the Animas Valley for the period 1948 through 1958.	8-41
8-13	Measured and simulated drawdown (in ft) for January 1955.	8-43
8-14	Distribution of transmissivity values after completion of the model calibration procedure.	8-44
8-15	Distribution of storage coefficient values after completion of the model calibration procedure.	8-45
8-16	Observed and simulated water-level elevations for January 1959.	8-47
8-17	Observed and simulated water-level elevations at well 24.20.22.222.	8-48
8-18	Observed and simulated water-level elevations at well 25.19.7.234.	8-49
8-19	Observed and simulated water-level elevations at well 16.10.16.422.	8-50

<u>Figure</u>		<u>Page</u>
8-20	Observed and simulated water-level elevations at well 27.19.19.433.	8-51
8-21	Location of wells and nodes in Figures 8-17 through 8-20 and corresponding grid blocks in the finite-difference mesh.	8-52
8-22	Observed and simulated water-level elevations in an east-west cross-section through the irrigation pumping center in April 1948.	8-54
8-23	Observed and simulated water-level elevations in an east-west cross-section through the irrigation pumping center in January 1955.	8-55
8-24	Observed and simulated water-level elevations in an east-west cross-section through the irrigation pumping center in January 1959.	8-56
8-25	Model sensitivity test for hydraulic head, pumping rate (Q), transmissivity (T), and storage coefficient (S) at pumping node 6-20.	8-58
8-26	Model sensitivity test for hydraulic head, transmissivity (T), and storage coefficient (S) at non-pumping node 6-26.	8-59
8-27	Errors in computed head due to an increase in initial water level of 16.4 feet at node 6-20.	8-61
8-28	Errors in computed head due to a 50 percent increase in transmissivity at node 6-20.	8-62
8-29	Errors in computed head due to a 50 percent increase in pumping rate at node 6-20.	8-63
8-30	Errors in computed head due to a 50 percent increase in storage coefficient at node 6-20.	8-64
8-31	Groundwater temperature map (in °C) based on data collected in 1980 and 1981.	8-76
8-32	Total dissolved solids concentrations map (in ppm) based on data collected in 1980 and 1981.	8-78
8-33	Total dissolved solids versus specific electrical conductivity.	8-79
8-34	Chloride concentration map (in ppm) based on data collected in 1980 and 1981.	8-80

<u>Figure</u>		<u>Page</u>
8-35	Sulfate concentration map (in ppm) based on data collected in 1980 and 1981.	8-81
8-36	Sodium concentration map (in ppm) based on data collected in 1980 and 1981.	8-82
8-37	Lithium concentration map (in ppm) based on data collected in 1980 and 1981.	8-83
8-38	Silica concentration map (in ppm) based on data collected in 1980 and 1981.	8-84
8-39	Ratio of equivalent weights of calcium to chloride based on data collected in 1980 and 1981.	8-85
8A-1	New Mexico well numbering system.	8-93

LIST OF TABLES

<u>Table</u>		<u>Page</u>
2-1	Distribution by county of oil and gas wells in New Mexico for which bottom-hole temperature data are available. . . .	2-3
2-2	Temperature gradients and projected surface temperatures based on bottom-hole temperatures of oil and gas wells. . .	2-8
2-3	Oil and gas wells in New Mexico with computed bottom-hole temperature gradients above 40°C/km.	2-10
2-4	Hot, flowing artesian wells in the San Juan Basin. . . .	2-17
3-1	Instrumental origin times, epicenters, and magnitudes for New Mexico earthquakes with $M_L \geq 1.5$ from 1978 through 1980.	3-4
5-1	Wells examined for temperature logging in Dona Ana County.	5-3
5-2	Wells examined for temperature logging in Grant County. . .	5-5
5-3	Wells examined for temperature logging in Hidalgo County. .	5-7
5-4	Wells examined for temperature logging in Luna County. . .	5-9
5-5	Wells examined for temperature logging in Sierra County. .	5-11
5-6	Measured temperature-depth data of the 13 wells logged in southwestern New Mexico.	5-13
7-1	Computed bottom-hole temperature gradients for wells in southwestern New Mexico.	7-43
7-2	Lithology of shallow temperature-gradient holes in the Faywood-Deming area.	7-74
7-3	Temperature-depth data for shallow temperature-gradient holes in the Faywood-Deming area.	7-76
7-4	Temperature-gradient, thermal-conductivity, and heat-flow data for shallow temperature-gradient holes in the Faywood-Deming area.	7-77
8-1	Irrigation data in the Animas Valley.	8-40
8-2	Chemical analyses (in ppm) of water from wells in the Animas Valley, Hidalgo County, New Mexico.	8-67
8-3	Field measurements of water from wells in the Animas Valley, Hidalgo County, New Mexico.	8-72

Chapter 1
Public and Technical Geothermal Resources of
New Mexico Maps*

Introduction

The purpose of the present study is to compile all of the geological, geophysical, and geochemical data pertaining to geothermal energy resources and to use these data in compiling a series of geothermal resource maps for the state of New Mexico. The map package consists of a user-oriented public map designed for use by the general public, and a series of technical maps designed primarily for use by the scientific community. Although the technical data are being compiled on the basis of their relevance to geothermal resources, the maps will serve the professional interests of the entire geological community and, therefore, have a much greater value than merely their depiction of geothermal energy resources in New Mexico.

Discussion

Public Map

This map has been published (Swanberg 1980) and is currently available at a scale of 1:500,000 from the New Mexico Energy Institute at New Mexico State University, Las Cruces, New Mexico 88003.

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

Technical Maps

The technical map series (scale 1:500,000) consists of a base map, five overlay maps, and several inset maps. The organization and status of these maps are as follows:

Late Tertiary and Quaternary Volcanic and Tectonic Data (J. Callender and W. Seager). This map is being used as the base map for the technical map series. All of the remaining maps are being prepared as overlays for this map. The map itself shows the distribution of late Tertiary and Quaternary faults, volcanic rocks, and volcanic centers. Also shown are the corresponding age dates. This map also depicts geothermal information, such as hot springs and known geothermal areas, and geographic data, such as cities, highways, topography, and townships. A complete draft of this map was produced and was reviewed, revised, and updated prior to being redrafted. This map will also contain several inset maps depicting geothermal information, which is not suitable for presentation at a scale of 1:500,000. These insets are statewide maps of heat flow (Swanberg 1979), seismic epicentral location (Sanford 1980, 1981), seismic risk (Algermissen and Perkins 1976), and oil and gas wells with abnormally high bottom-hole temperatures (Chaturvedi 1980, 1981). This entire package was forwarded to NOAA for map production in mid-June 1981.

Hydrologic Data (P. Morgan, V. Harder, J. Callender, and C. A. Swanberg).

This map will contain three data sets. The first data set is the distribution of the shallow Cenozoic and the deep Cenozoic sedimentary basins. This map is an update of an earlier map by Swanberg (1979), which had been published prior to the extensive gravity modeling of Birch (1980). This data set, which is being prepared as part of the current project, has been completed.

The second data set is the distribution of groundwater constrictions and groundwater barriers (Morgan et al. 1981). This data set was completed in early May 1981 and will be transferred to the sedimentary basin map as soon as that map becomes available.

The third data set consists of temperature-gradient contours for those sedimentary basins where adequate temperature data exist. All of the raw data for this effort have been collected, but the data have not been screened nor contoured. This package will probably not be available until late 1981.

Geochemical and Geoelectric Data (C. A. Swanberg, G. P. Landis, and G. R. Jiracek). This map will utilize a stiff diagram to depict the geochemistry of representative geothermal waters of New Mexico. Also shown will be the Na-K-Ca and silica geotemperatures for these waters, as well as the oxygen and hydrogen stable isotope shifts. The map will also show regional variations in oxygen and hydrogen isotopic data, and the regions where groundwater chemical data indicate a possible geothermal component. Those areas where deep electrical studies (both passive and active) have been conducted will also be depicted. All of the data for this map have been collected but the map has not been put into draft form nor critically reviewed. This package will probably not be available until late 1981.

Bouguer Gravity Map of New Mexico (G. R. Keller and L. Cordell). This map is being produced by the U.S. Geological Survey and will be made available for the present map series. The data base has been updated during 1981 but not screened for erroneous points nor contoured. This map is an update of a previous map by Cordell et al. (1978), which was published at a scale of 1:1,000,000. The map is scheduled for completion by late summer 1981.

Aeromagnetic Map of New Mexico (L. Cordell). Preparation of this map is part of the 1982 program. Work has not yet begun and is not scheduled for completion until spring 1982.

Lineament Map of New Mexico (L. Lepley). A preliminary copy of this map has been prepared and is currently being finalized. This material is summarized in Chapter 4.

All of the aforementioned maps will be documented with squibs, references, explanations, and other material, which will enhance the utility of the map series. The raw data will be incorporated into an accompanying publication along with a brief description of each data set.

References

- Algermissen, S. T., and Perkins, D. M., 1976, A probabilistic estimate of maximum acceleration in rock in the contiguous United States: U.S. Geological Survey, Open-File Report, 76-416, 45 pp.
- Birch, F., 1980, personal communication, U.S. Geological Survey.
- Chaturvedi, L. N., 1980, Geothermal hydrology, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1979: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 8/1 - 8/22.
- Chaturvedi, L. N., 1981, Locating geothermal anomalies using bottom-hole temperatures from oil and gas wells in New Mexico, in Icerman, L., and Starkey, A., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1981: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 2/1 - 2/22 [In Press].
- Cordell, L., Keller, G. R., and Hildebrand, T. G., 1978, Gravity of the Rio Grande Rift: U.S. Geological Survey, map, scale 1:1,000,000.
- Morgan, P., Harder, V., Daggett, P. H., and Swanberg, C. A., 1981, Model for origin and distribution of low-temperature geothermal resources in Rio Grande Rift, Southern Rocky Mountain Complex (abs.): American Association of Petroleum Geologists, Rocky Mountain Section 29th Annual Meeting, Albuquerque, Proceedings.
- Sanford, A. R., 1980, Earthquake activity in New Mexico, 1849-1977, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1979: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 3/1 - 3/26.
- Sanford, A. R., 1981, Updating of New Mexico seismic data, in Icerman, L., and Starkey, A., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1981: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 3/1 - 3/8.
- Swanberg, C. A., 1979, Chemistry of thermal and non-thermal groundwaters in the Rio Grande Rift and adjacent tectonic provinces, in Riecker, R. E., ed., Rio Grande Rift, tectonics and magmatism: American Geophysical Union, Washington, D.C., p. 279-288.
- Swanberg, C. A., compiler, 1980, Geothermal resources of New Mexico: New Mexico Energy Institute at New Mexico State University, map, scale 1:500,000.

Chapter 2

Locating Geothermal Anomalies Using Bottom-Hole Temperatures from Oil and Gas Wells in New Mexico*

Introduction

Temperatures at the bottom of oil and gas wells are routinely measured during the logging of a well. These measurements are used in the quantitative interpretation of geophysical logs, especially those which measure properties that are affected by temperature (e.g., electrical resistivity). Thus, bottom-hole temperatures are typically recorded on the geophysical logs of oil and gas wells. Since the New Mexico Oil Conservation Division of the New Mexico Department of Energy and Minerals maintains logs of all oil and gas wells drilled in New Mexico, these data may be obtained and analyzed to assist in locating areas of geothermal potential, which are not manifested by a hot spring or a hot well (i.e., a blind geothermal anomaly).

The recorded bottom-hole temperature does not generally indicate the actual temperature at that depth because the temperature is generally measured soon after the well is drilled, before the well reaches thermal equilibrium. However, an analysis of a large number of bottom-hole temperature measurements may yield meaningful results. Jaeger (1961) showed that temperature departures are relatively small under ordinary conditions of rotary drilling. Several other workers, notably Schoepel and Gilarranz (1966), Tanner (1976), and Hodge et al. (1979), have shown that bottom-hole temperatures measured in oil and gas wells may be used as reliable data to estimate regional variations

*The principal author of Chapter 2 is Dr. Lokesh Chaturvedi, Associate Professor of Earth Sciences and Civil Engineering, New Mexico State University.

in temperature gradients. Giardina and Couley (1978) have applied similar methods to temperatures measured in water wells.

This study involved: (1) collecting data on the location, depth, and bottom-hole temperature for each well; (2) drawing depth versus temperature plots using bottom-hole temperatures and the depths of measurement; and (3) computing a temperature gradient for each well using the bottom-hole and projected surface temperatures. A map showing computed anomalous geothermal gradients for New Mexico was also prepared.

Data Collection and Analysis

Data Sources

The New Mexico Oil Conservation Division (OCD) maintains files containing geophysical logs and other pertinent data on each oil and gas well drilled in New Mexico. These data are kept in OCD Offices located in Santa Fe, Aztec, and Artesia. A total of 15,732 bottom-hole temperatures were obtained from these files.

Table 2-1 shows the distribution of the number of wells in each county for which bottom-hole temperature data are available and were collected. Since most oil and gas well drilling activity has been confined to the northwest and southeast parts of the state (i.e., the San Juan and Permian basins), most of the data refer to locations in counties in these areas. No data are available for two counties, namely, Los Alamos and Taos, which is a limitation of this research methodology. Los Alamos County contains two of the most promising geothermal areas in New Mexico in the Department of Energy Hot Dry Rock Project at Fenton Hill and the Baca Location No. 1 Known Geothermal Resource Area. However, because of the lack of oil and gas

Table 2-1. Distribution by county of oil and gas wells in New Mexico for which bottom-hole temperature data are available.

<u>Region and County</u>	<u>Number of Wells</u>
San Juan Basin	
McKinley	263
Rio Arriba	4,625
San Juan	7,850
Sandoval	298
Permian Basin	
Chaves	543
Lea	892
Roosevelt	995
Rest of New Mexico	
Bernalillo	7
Catron	15
Colfax	15
Curry	6
DeBaca	16
Dona Ana	8
Grant	1
Guadalupe	32
Harding	22
Hidalgo	10
Lincoln	2
Los Alamos	- *
Luna	6
Mora	14
Otero	20
Quay	15
San Miguel	7
Santa Fe	2
Sierra	13
Socorro	11
Taos	- *
Torrance	6
Union	15
Valencia	<u>23</u>
Total	15,732

*No data are available for Taos and Los Alamos counties.

drilling activity in Los Alamos County, these areas do not appear as an anomaly in a map generated from oil and gas well bottom-hole temperature data.

Geothermal Gradients

Three categories of data were entered into the computer files, representing the San Juan Basin, the Permian Basin, and all other areas of New Mexico. Temperature versus depth curves were generated for each of these areas and are shown in Figures 2-1, 2-2, and 2-3 for the San Juan Basin, the Permian Basin, and the remainder of the state, respectively. Maximum, minimum, and best-fit temperature gradients, as well as projected surface temperatures, for each of the three regions are shown in Table 2-2.

The Permian Basin shows the lowest temperature gradients and no distinct geothermal anomalies. The data for areas outside the Permian and San Juan basins show a best-fit temperature gradient of $20.5^{\circ}\text{C}/\text{km}$. The highest best-fit temperature gradient is found in the San Juan Basin area in northwest New Mexico. This observation should not be interpreted to imply that the San Juan Basin area is the best prospective location for geothermal resources in New Mexico. Instead, compared to the Permian Basin, the San Juan Basin represents a better geothermal prospect. The data for the rest of the state are too sparse to yield meaningful comparative results.

Location of Geothermal Anomalies

Geothermal gradients for individual well sites were computed by assuming a linear gradient between an extrapolated surface temperature and the recorded bottom-hole temperature. In a previous work (Chaturvedi and Lory 1980), a mean annual surface temperature was obtained from reported ambient air temperature measurements. In this analysis, however, an effective surface

Figure 2-1. Temperature vs. depth distribution for oil and gas wells located in the San Juan Basin. The maximum, minimum, and best-fit lines refer to visually-selected, representative temperature gradients.

Figure 2-2. Temperature vs. depth distribution for oil and gas wells located in the Permian Basin. The maximum, minimum, and best-fit lines refer to visually-selected, representative temperature gradients.

Figure 2-3. Temperature vs. depth distribution for oil and gas wells in New Mexico located in areas other than the San Juan and Permian basins. The maximum, minimum, and best-fit lines refer to visually-selected, representative temperature gradients.

Table 2-2. Temperature gradients and projected surface temperatures based on bottom-hole temperatures of oil and gas wells.

<u>Region</u>	Bottom-Hole Temperature Gradient* (°C/km)			<u>Projected Surface Temperature (°C)</u>
	<u>Maximum</u>	<u>Minimum</u>	<u>Best-Fit</u>	
San Juan Basin	38.9	20.8	27.8	18
Permian Basin	19.75	9.9	16.0	21
Rest of New Mexico	28.0	13.6	20.5	20

*The calculation of maximum, minimum, and best-fit temperature gradients is based on visually-selected lines constructed on the respective temperature vs. depth distributions.

temperature for each region was determined by projecting a best-fit temperature gradient line to the surface. These effective surface temperatures are given in Table 2-2 and are higher than the corresponding mean annual ambient air temperatures. Thus, the computed temperature gradients should represent conservative values.

Table 2-3 shows the locations and computed geothermal gradients for those wells which have a computed bottom-hole temperature gradient of $40^{\circ}\text{C}/\text{km}$ or higher. These data have been sorted into temperature gradient categories of 40 to 60, 60 to 80, 80 to 100, and over $100^{\circ}\text{C}/\text{km}$ (see Figure 2-4). A single-point anomaly, particularly in the lower computed gradient range, may not signify a geothermal anomaly. However, a cluster of anomalous points, particularly those showing relatively high computed temperature gradients, most likely represents an anomalous geothermal area which should be explored further.

Artesian Hot Water Wells

During the course of this investigation, a number of reported hot water or hot gas wells were checked in the field. All these wells are located in the San Juan Basin. Seven of these wells are flowing hot water wells with temperatures exceeding 60°C at the wellhead. The available data on these wells are summarized in Table 2-4 and the well locations are shown in Figure 2-4. Photographs of the Gallo Wash No. 1 Well and the hot water discharge from the Mesa Petroleum Company Well No. 36-E are shown in Figures 2-5 and 2-6, respectively.

Table 2-3. Oil and gas wells in New Mexico with computed bottom-hole temperature gradients above 40°C/km.

County	Latitude	Longitude	Township/Range/ Section	Temperature (°F)	Temperature (°C)	Depth (ft)	Depth (m)	Bottom-Hole Temperature Gradient* (°C/km)
McKinley	35.9357	107.9772	20N 11W 26	90	32.2	956	291.4	48.8
	35.8905	107.4104	19N 5W 7	118	47.8	2252	686.4	43.3
	35.7348	107.7087	17N 8W 5	117	47.2	1631	497.1	58.8
	35.7206	107.7087	17N 8W 8	132	55.6	2967	904.3	41.5
Rio Arriba	36.9702	107.1173	32N 3W 23	117	47.2	1207	367.9	79.4
	36.9118	107.3462	31N 5W 10	251	122.2	8340	2542.0	41.0
	36.8858	106.8491	31N 1E 20	171	77.2	1856	565.7	104.7
	36.8411	107.5407	30N 7W 2	284	140.0	5699	1737.1	70.2
	36.8405	107.3651	30N 5W 4	251	121.7	8031	2447.8	42.4
	36.7110	107.2409	29N 4W 22	208	97.8	6154	1875.7	42.5
	36.6821	107.4192	29N 6W 36	194	90.0	5688	1733.7	41.5
	36.6663	107.0295	28N 2W 3	78	25.6	373	113.7	66.5
	36.6312	107.5280	28N 7W 25	187	86.1	5380	1639.8	41.5
	36.6029	107.2935	27N 4W 6	90	32.2	1098	334.7	42.5
	36.6029	107.4197	27N 6W 1	145	62.8	3381	1030.5	43.5
	36.5452	107.2753	27N 4W 29	163	72.8	3932	1198.5	45.7
	36.5452	107.5432	27N 7W 26	142	61.1	3139	956.8	45.1
	36.5452	107.5969	27N 7W 29	135	57.2	2920	890.0	44.1
	36.5006	106.8575	26N 1E 8	107	41.7	1921	585.5	40.4
	36.5006	106.8575	26N 1E 8	130	54.4	2965	903.7	40.3
	36.5000	107.4002	26N 5W 7	242	116.7	7594	2314.7	42.6
	36.4859	107.5432	26N 7W 14	118	47.8	2354	717.5	41.5
	36.4418	107.1826	26N 3W 31	182	83.3	3942	1201.5	54.4
	36.4418	107.4902	26N 6W 32	130	54.4	2877	876.9	41.6
	36.4123	107.2579	25N 4W 9	200	93.3	3947	1203.0	62.6
	36.3699	107.1826	25N 3W 30	85	29.4	425	129.5	88.4
	36.3693	107.4002	25N 5W 30	168	58.9	2657	809.9	50.5
	36.3693	107.4197	25N 6W 25	122	50.0	2505	763.5	41.9

Table 2-3. (continued).

County	Latitude	Longitude	Township/Range/ Section	Temperature		Depth		Bottom-Hole Temperature Gradient* (°C/km)
				(°F)	(°C)	(ft)	(m)	
Rio Arriba	36.3371	107.2056	24N 4W 1	168	75.6	3319	1011.6	56.9
	36.3077	107.1603	24N 3W 16	134	56.7	3145	958.6	40.3
	36.2517	106.9099	23N 1W 2	92	33.3	1188	362.1	42.4
	36.2517	107.0533	23N 2W 4	133	56.1	3059	932.4	40.9
Sandoval	36.1940	107.4750	23N 6W 28	150	65.6	2802	854.0	55.7
	36.1504	107.2276	22N 4W 8	74	23.3	371	113.1	47.2
	36.1216	107.5110	22N 6W 19	154	67.8	2050	624.8	79.7
	36.0780	107.5810	21N 7W 4	95	35.0	1100	335.3	50.7
	36.0639	107.3496	21N 5W 10	115	46.1	2271	692.2	40.6
	36.0057	107.4030	21N 5W 31	90	32.2	865	263.7	53.9
	35.9362	107.2266	20N 4W 26	79	26.1	649	197.8	41.0
	35.8747	107.2789	19N 4W 17	90	32.2	986	300.5	47.3
San Juan	36.9994	107.6281	32N 8W 12	260	126.7	8701	2652.1	41.0
	36.9949	107.5726	32N 7W 9	250	121.1	8015	2443.0	42.2
	36.9870	108.1516	32N 13W 13	120	48.9	499	152.1	203.1
	36.9870	108.1516	32N 13W 13	183	83.9	3085	940.3	70.1
	36.9870	108.1682	32N 13W 14	82	27.8	327	99.7	98.1
	36.9870	108.1682	32N 13W 14	180	82.2	2852	869.3	73.9
	36.9858	107.9051	32N 10W 17	187	86.1	5414	1650.2	41.3
	36.9836	107.4639	32N 6W 16	195	90.6	5440	1658.1	43.8
	36.9802	107.5186	32N 7W 13	247	119.4	8205	2500.9	40.6
	36.9751	108.1848	32N 13W 22	142	61.1	3421	1042.7	41.3
	36.9717	107.7832	32N 9W 21	260	126.7	8593	2619.1	41.5
	36.9728	108.7672	32N 18W 20	90	32.2	1149	350.2	40.6
	36.9706	107.8697	32N 10W 22	192	88.9	5554	1692.9	41.9
	36.9655	107.5907	32N 7W 20	196	91.1	5723	1744.4	41.9

Table 2-3. (continued).

County	Latitude	Longitude	Township/Range/ Section	Temperature		Depth		Bottom-Hole Temperature Gradient* (°C/km)
				(°F)	(°C)	(ft)	(m)	
San Juan	36.9638	108.6094	32N 17W 27	100	37.8	1352	412.1	48.0
	36.9654	107.8351	32N 10W 25	194	90.0	5642	1719.7	41.9
	36.9548	109.0318	32N 21W 26	80	26.7	586	178.6	48.5
	36.9491	108.6274	32N 17W 33	93	33.9	1261	384.4	41.3
	36.9485	108.2901	32N 14W 34	127	52.8	2626	800.4	43.5
	36.9485	108.2555	32N 14W 36	127	52.8	2603	793.4	43.8
	36.9434	107.6447	32N 8W 35	189	87.2	5426	1653.8	41.9
	36.9429	108.0609	32N 12W 35	165	73.9	2983	909.2	61.5
	36.9321	108.5796	31N 17W 1	102	38.9	1263	385.0	54.3
	36.9321	108.5796	31N 17W 1	96	35.6	1283	391.0	44.9
	36.9321	108.5796	31N 17W 1	97	36.1	1344	409.7	44.2
	36.9321	108.5796	31N 17W 1	96	35.6	1390	423.7	41.4
	36.9321	108.6502	31N 17W 5	97	36.1	1207	367.9	49.2
	36.9287	108.0159	31N 11W 5	186	85.6	5425	1653.5	40.9
	36.9186	108.5616	31N 16W 7	102	38.9	1402	427.3	48.9
	36.9186	108.5616	31N 15W 7	114	45.6	1790	545.6	50.5
	36.9101	107.4369	31N 6W 11	250	121.1	8119	2474.7	41.7
	36.9044	108.5443	31N 16W 17	119	48.3	1790	545.6	55.6
	36.9038	108.3635	31N 15W 13	120	48.9	2147	654.4	47.2
	36.8993	107.8047	31N 9W 17	192	88.9	5790	1764.8	40.2
	36.8891	108.5796	31N 17W 24	113	45.0	1536	468.2	57.7
	36.8756	108.5090	31N 16W 27	113	45.0	1499	456.9	59.1
	36.8756	108.5443	31N 16W 29	96	35.6	1364	415.7	42.2
	36.8756	108.5616	31N 16W 30	100	37.8	1391	424.0	46.7
	36.8756	108.5616	31N 16W 30	95	35.0	1376	419.4	40.5
	36.8607	108.5616	31N 16W 31	95	35.0	1318	401.7	42.3
	36.8607	108.5616	31N 16W 31	95	35.0	1341	408.7	41.6
	36.8607	108.5443	31N 16W 32	93	33.9	1271	387.4	41.0
	36.8607	108.5443	31N 16W 32	96	35.6	1302	396.8	44.2
	36.8607	108.5256	31N 16W 33	108	42.2	1292	393.8	61.5

Table 2-3. (continued).

County	Latitude	Longitude	Township/Range/ Section	Temperature		Depth		Bottom-hole Temperature Gradient* (°C/km)
				(°F)	(°C)	(ft)	(m)	
San Juan	36.8603	108.5976	31N 17W 35	90	32.2	961	292.9	48.6
	36.8563	107.7340	31N 9W 36	142	61.1	3085	940.3	45.9
	36.8563	107.6426	31N 8W 35	148	64.4	3552	1082.6	42.9
	36.8444	108.6467	30N 17W 5	100	37.8	1363	415.4	47.6
	36.8439	108.5062	30N 16W 3	113	45.0	1671	509.3	53.0
	36.8439	108.5254	30N 16W 4	93	33.9	1287	392.3	40.5
	36.8439	108.5415	30N 16W 5	92	33.3	1171	356.9	43.0
	36.8439	108.5415	30N 16W 5	93	33.9	1189	362.4	43.8
	36.8439	108.5415	30N 16W 5	90	32.2	1150	350.5	40.6
	36.8162	108.5254	30N 16W 16	110	43.3	1323	403.3	62.8
	36.7964	107.7015	30N 8W 20	180	82.2	4795	1461.5	43.9
	36.7964	107.6842	29N 9W 21	188	86.7	5054	1540.5	44.6
	36.7964	107.8220	30N 9W 19	184	84.4	5257	1602.3	41.5
	36.7828	107.7333	30N 9W 25	120	48.9	2465	751.3	41.1
	36.7738	108.5588	30N 16W 31	87	30.6	640	195.1	64.4
	36.7738	108.5415	30N 16W 32	100	37.8	1590	484.6	40.8
	36.7687	107.9106	30N 10W 32	124	51.1	2427	739.7	44.8
	36.7559	107.8192	29N 9W 6	184	84.4	4270	1301.5	51.1
	36.7559	107.8192	29N 9W 6	182	83.3	4584	1397.2	46.8
	36.7551	107.9065	29N 10W 5	115	46.1	2268	691.3	40.7
	36.7426	108.7950	29N 17W 12	90	32.2	1005	306.3	46.4
	36.7426	108.7950	29N 17W 12	90	32.2	940	286.5	49.6
	36.7426	108.7950	29N 17W 12	90	32.2	963	293.5	48.5
	36.7426	108.7950	29N 17W 12	91	32.8	930	283.5	52.1
	36.7426	108.7950	29N 17W 12	88	31.1	959	292.3	44.9
	36.7421	107.8019	29N 9W 8	173	78.3	4633	1412.1	42.7
	36.7415	107.8891	29N 10W 9	132	55.6	2321	707.4	53.1
	36.7285	108.7950	29N 17W 13	91	32.8	993	302.7	48.8
	36.7274	107.7666	29N 9W 15	76	24.4	270	82.3	78.3
	36.7268	107.8351	29N 10W 13	132	55.6	2169	661.1	56.8

Table 2-3. (continued).

County	Latitude	Longitude	Township/Range/ Section	Temperature (°F)	Temperature (°C)	Depth (ft)	Depth (m)	Bottom-Hole Temperature Gradient* (°C/km)
San Juan	36.7262	108.5602	29N 16W 19	122	50.0	1253	381.9	83.8
	36.7262	108.5602	29N 16W 19	96	35.6	889	271.0	64.8
	36.7132	107.7492	29N 9W 23	132	55.6	2451	747.1	50.3
	36.7121	107.6634	29N 8W 22	135	57.2	3175	967.7	40.5
	36.6985	107.7306	29N 9W 25	260	126.7	7029	2142.4	50.7
	36.6985	107.7846	29N 9W 28	146	63.3	3690	1124.7	40.3
	36.6968	107.7132	29N 8W 30	190	87.8	5715	1741.9	40.1
	36.6838	107.6440	29N 8W 35	195	90.6	5576	1699.6	42.7
	36.6838	107.8351	29N 10W 36	114	45.6	2048	624.2	44.1
	36.6838	107.8351	29N 10W 36	109	42.8	1885	574.5	43.1
	36.6832	107.7160	29N 8W 31	180	82.2	4579	1359.7	46.0
	36.6832	107.7160	29N 8W 31	220	104.4	6938	2114.6	40.9
	36.6832	107.6634	29N 8W 34	135	57.2	3185	970.8	40.4
	36.6753	107.8801	28N 10W 10	123	50.6	2075	632.5	51.5
	36.6731	107.9854	28N 10W 10	108	42.2	1718	523.6	46.2
	36.6476	107.9348	28N 10W 19	110	43.3	2036	620.6	40.8
	36.6476	107.9348	28N 10W 19	117	47.2	2056	626.7	46.6
	36.6454	107.9854	28N 11W 22	108	42.2	1670	509.0	47.6
	36.6272	107.6343	28N 8W 25	120	48.9	2529	770.8	40.1
	36.5871	107.7049	27N 8W 7	152	66.7	2960	902.2	53.9
	36.5724	107.7382	27N 9W 13	117	47.2	2154	656.5	44.5
	36.5747	107.9342	27N 10W 18	108	42.2	1663	506.9	47.8
	36.5628	108.0235	27N 11W 20	210	98.8	6564	2000.7	40.4
	36.5181	108.0609	26N 12W 1	112	44.4	1519	463.0	57.1
	36.5164	107.9369	26N 10W 6	120	48.9	2128	648.6	47.6
	36.5051	108.3254	26N 14W 9	100	37.8	1354	412.7	47.9
	36.5028	108.1661	26N 13W 12	100	37.8	1308	398.7	49.6
	36.4887	108.0782	26N 12W 14	80	26.7	387	118.0	73.5
	36.4604	108.1481	26N 12W 30	103	39.4	1297	395.2	54.3

Table 2-3. (continued).

County	Latitude	Longitude	Township/Range Section	Temperature		Depth		Bottom-Hole Temperature Gradient* (°C/km)
				(°F)	(°C)	(ft)	(m)	
San Juan	36.4598	108.1294	26N 12W 29	94	34.4	1306	398.0	41.3
	36.4598	108.1294	26N 12W 29	93	33.9	1290	393.2	40.4
	36.4587	107.9889	26N 11W 27	152	66.7	3185	970.8	50.1
	36.4451	108.2368	20N 13W 32	120	48.8	1592	485.2	63.7
	36.4282	107.9882	25N 11W 3	100	37.8	974	296.9	66.6
	36.1391	107.7084	22N 8W 17	98	36.7	1471	448.4	41.6

*An effective surface temperature of 18°C, based on the projection of a best-fit temperature gradient line to the surface, was used in the bottom-hole temperature gradient computations.

Figure 2-4. Locations of oil and gas wells in New Mexico with computed anomalous geothermal gradients based on bottom-hole temperatures.

Table 2-4. Hot, flowing artesian wells in the San Juan Basin.

Owner and Well Name	Location	Elevation of Wellhead (ft above m.s.l.)	Producing Horizon	Temperature and Remarks
Mesa Petroleum Co. State Comm. AC#36-E	1750' FNL, 1500' FEL Sec 32, T31N, R8W	6322	Pictured Cliffs Basin (Dakota sandstone)	Temperatures recorded, 47.7°C at 3595 ft (10/14/80), 78°C at 7740 ft (10/20/80); flowing wellhead temperature, 65.5°C
Union Texas Petroleum Johnston Fed#4	Sec 33, T31N, R9W	6203	Producing gas from 4645 to 5360 ft below surface	Steam was encountered at ~ 5000 ft; wellhead temperature, 71°C
Mesa Petroleum Co. State Comm. J#6	Sec 36, T31N, R9W	----	Pictured Cliffs Basin (Dakota sandstone); 4493 to 5191 ft below surface	Total depth, 5200 ft; wellhead temperature, 65.5°C
Alameda Coal Co. Gallo Wash No. 1	Sec 16, T21N, R9W	----	Entrada and westwater	Wellhead temperature, 62.2°C; total dissolved solids, 3700 mg/l; total depth = 5348 ft
C and P No. 1	Sec 16, T21N, R9W	6380	Total depth, 5694 ft	Wellhead temperature, 62.2°C
El Paso Natural Gas	Sec 4, T23N, R14W	----	Total depth, 5200 ft	Wellhead temperature, 61°C; flow rate, 500 gpm
Apache Oil Co. No. 1 (Foshay)	Sec 9, T23N, R13W	----	----	----

Figure 2-5. Artesian hot water (62°C) discharge from Gallo Wash No. 1 Well in the southeastern part of San Juan County. The total depth of the well is 5348 feet (see Table 2-4, fourth entry.)

Figure 2-6. Artesian hot water (65.5°C) discharge from Mesa Petroleum Company Well near Navajo Lake in the northeastern part of San Juan County. The total depth of the well is 7740 feet (see Table 2-4, first entry).

Conclusions and Recommendations

Delineating broad anomalous geothermal regions in previously unexplored areas, where large numbers of oil and gas wells have been drilled, by computing bottom-hole temperature gradients appears to be an inexpensive and informative research methodology. However, this approach should be used with caution and little reliance should be placed on the identification of an isolated single-point anomaly.

Broad areas of high gradient anomalies, particularly, in northwestern New Mexico should be further explored for geothermal resources. The coincidence of hot water wells in the general area of the high computed bottom-hole temperature gradients suggests strongly that useful geothermal resources are located in these areas.

Acknowledgements

The data used in this report were collected at the New Mexico Oil Conservation Division Offices in Aztec, Santa Fe, and Artesia. Special thanks are due to Mr. Frank Chavez and Mr. Carl Ulvog for their help and information during the data collection process.

Mr. Jeffrey K. Lory worked as a Research Assistant on this project. He collected most of the data, helped in the analysis, and took the two photographs of the hot water wells.

References

- Chaturvedi, L., and Lory, J. K., 1980, A preliminary evaluation of geothermal potential of San Juan Basin, New Mexico, using bottom-hole temperatures from oil and gas wells: Geothermal Resources Council, Transactions, v. 4, p. 21-25.
- Hodge, D. S., Hilfiker, K., Morgan, P., and Swanberg, C. A., 1979, Preliminary geothermal investigations in New York State: Geothermal Resources Council, Transactions, v. 3, p. 317-320.
- Jaeger, J. C., 1961, The effect of the drilling fluid on temperatures measured in bore holes: Journal of Geophysical Research, v. 66, p. 563-569.
- Schoeppel, R. J., and Gilarranz, S., 1966, Use of well log temperatures to evaluate regional geothermal gradients: Journal of Petroleum Technology, v. 18, p. 667-673.
- Tanner, W. F., 1976, Geothermal exploration from deep-well data: Gulf Coast Association of Geological Societies, Transactions, v. 26, p. 65-68.

Chapter 3

Updating of New Mexico Seismic Data*

Introduction

In the last few years, a number of papers on seismic activity within New Mexico have been jointly authored by investigators from Los Alamos National Laboratory (LANL), U. S. Geological Survey-Albuquerque Seismological Laboratory (ASL), and New Mexico Institute of Mining and Technology (NMT). The latest paper by Sanford, Olsen, and Jaksha (1981) lists, analyzes, and discusses earthquake activity in New Mexico for the period 1849 through 1977. This material on seismic activity in New Mexico, 1978 through 1980, is an extension of the earlier paper, but with little analysis or discussion. Like all previous reports and papers, it is primarily a collaborative effort of groups at LANL, ASL, and NMT.

Data

Sources of Information

The principal sources of data for this report were:

- (1) Wechsler, Cash, Olsen, McFarland, and Wolff (1980a, 1980b, 1980c, 1981a, 1981b). This is a series of progress reports published by the Los Alamos National Laboratory on earthquakes located by the LANL seismic network in northcentral New Mexico.
- (2) Jaksha and Locke (1981). This is one of a series of open-file reports released by the U. S. Geological Survey-Albuquerque Seismological Laboratory on the earthquakes located by a U. S. Geological Survey (USGS) array in central New Mexico. In addition, the Albuquerque Seismological Laboratory provided unpublished data on shocks which occurred in 1979 and 1980.

*The principal author of Chapter 3 is Dr. Allan R. Sanford, Professor of Geophysics, Geoscience Department and Geophysical Research Center, New Mexico Institute of Mining and Technology.

- (3) The University of Texas at El Paso. During the period May 1978 through January 1981, Keller at this university submitted a series of reports to the Sandia National Laboratories on earthquakes located or detected by arrays located on the Central Basin Platform in west Texas and southeastern New Mexico.
- (4) Dumas (1981). This is a summary report of earthquakes located or detected by seismographs operated in west Texas by the University of Texas, Galveston Geophysics Laboratory.
- (5) U. S. Geological Survey, National Earthquake Information Service, Preliminary Determination of Epicenters, Monthly Listings for the Period 1978-1980.
- (6) Texas Tech University Seismological Observatory. Shurbet provided P and S arrival-time readings of New Mexico earthquakes from the Texas Tech stations for the Period 1978-1980.
- (7) Sanford, Sandford, Wallace, Barrows, Sheldon, Ward, Johansen, and Merritt (1980). This is a report on seismological studies of a 300-km radius area centered on a proposed nuclear waste disposal site in southeastern New Mexico.

Procedure

Lists of origin times, epicenters, and magnitudes from the above reports and organizations were searched for New Mexico earthquakes whose local magnitudes (M_L) equaled or exceeded 1.5, which is the minimum magnitude event considered in previous compilations (Sanford, Olsen, and Jaksha 1981). The magnitudes calculated by LANL, USGS, and ASL were reduced by 0.5 units to conform with magnitudes determined by the group at NMT. The 0.5 difference in magnitudes was established in an earlier study by Sanford, Olsen, and Jaksha (1981).

Because the available listings of earthquakes did not provide complete coverage of the state, particularly the southern half, seismic records and listed seismic readings from several sources were examined for possible New Mexico earthquakes. Approximately 60 additional seismic events were investigated but most were rejected from the final listing because the magnitudes were less than 1.5 or the epicenters were outside the boundaries of the state.

Parameters for New Mexico earthquakes (with local magnitudes, $M_L \geq 1.5$) that occurred in the three-year interval, 1978 through 1980, are given in Table 3-1. Also listed are the organizations whose epicenter coordinates, origin times, and magnitudes were used. In general, if an earthquake had an epicenter within either the ASL or the LANL arrays, the epicenters determined by those organizations were selected. In several cases, data from ASL and LANL were combined with a few additional readings and an epicenter was calculated by NMT.

Discussion

Level of Earthquake Activity

An unexpected result of this study was the low level of seismic activity; namely seven earthquakes in 1978, seven in 1979, and nine in 1980. For the previous three years and the same cut-off magnitude ($M_L \geq 1.5$), the numbers were 22 in 1975, 33 in 1976, and 15 in 1977 (Sanford, Olsen, and Jaksha 1981). The separate listings of earthquakes by LANL and USGS also show the same pattern of activity for shocks with $M_L \geq 1.5$. Thus, the decrease in seismic activity, which may have started in 1977, is real and not a failure of the compilation procedure. Other years with levels of activity nearly the same or lower than 1978, 1979, and 1980 were 1964, 1967, 1968, 1969, and 1970 (Sanford, Olsen, and Jaksha 1981). Therefore, the three-year period, 1978 through 1980, cannot be considered unusual for New Mexico.

Geographic Distribution of Activity

Most of the earthquakes in the 1978 through 1980 period occurred within or near the boundaries of the Rio Grande Rift (see Figure 3-1). The highest concentration of earthquake activity was in the central part of the rift near

Table 3-1. Instrumental origin times, epicenters, and magnitudes for New Mexico earthquakes with $M_L \geq 1.5$ from 1978 through 1980. Reporting organizations: NMT (New Mexico Institute of Mining and Technology), USGS (U.S. Geological Survey), LANL (Los Alamos National Laboratory), and ASL (Albuquerque Seismological Laboratory).

Date Yr/Mo/Da	Origin Time (GMT)	Latitude North	Longitude West	Located by				Magnitude (M_L)
				NMT	USGS	LANL	ASL	
78 01 19	03:42:37.4	32.5	103.8	X				2.3*
78 03 07	00:42:39.3	33.77	106.56		X			1.6****
78 04 07	00:57:39.8	32.0	106.0	X				2.3*
78 06 08	10:09:48.6	36.82	106.98			X		1.7***
78 07 21	05:02:36.3	34.68	105.09	X				2.0****
78 10 24	00:53:00.6	32.67	108.70	X				2.4*
78 12 30	12:11:21.6	34.11	106.99				X	1.5****
79 03 05	13:00:02.7	36.38	106.17			X		2.0***
79 03 30	10:41:54.6	35.12	106.79				X	1.7***
79 09 19	05:39:05.3	36.36	103.72			X		1.8***
79 10 11	22:32:25.3	37.03	106.87			X		1.5***
79 10 20	08:02:54.1	33.98	106.78		X			1.7***
79 10 20	21:05:34.0	33.90	106.72	X				2.9*
79 10 25	22:12:08.7	34.05	107.05	X				3.0*
80 01 21	00:47:50.0	32.4	106.3	X				1.8*
80 02 15	11:52:34.8	34.56	106.91	X				2.6*
80 02 28	16:39:45.2	34.42	107.00				X	3.3*
80 03 22	00:49:12.5	34.60	105.92		X			2.9**
80 09 11	17:34:37.5	36.46	105.19		X			2.6**
80 09 11	18:09:06.9	35.42	107.36				X	1.5***
80 09 12	19:22:18.1	36.39	105.66			X		2.2***
80 09 12	21:37:33.7	36.51	105.13			X		2.3***
80 09 18	11:39:47.4	34.24	106.65	X				1.8***

* NMT Magnitude
 ** USGS Magnitude -0.5
 *** LANL Magnitude -0.5
 **** ASL Magnitude -0.5

Socorro ($\sim 34^{\circ}\text{N}$, $\sim 107^{\circ}\text{W}$). The Rio Grande Rift, and particularly the section near Socorro, is historically the most seismically active area in the state (Sanford, Olsen, and Jaksha 1979, 1981). The concentration of earthquake activity near Socorro is believed to be the result of injection of magma into the crust (Sanford et al. 1977).

Acknowledgement

This material was prepared at NMT (with a great deal of help from graduate research assistants Robert Onderko, Jeffrey Roach, and Daniel Wieder) and we are responsible for any errors or omissions.

References

- Dumas, D., 1981, Summary of local and regional earthquakes (S-P 30 sec) recorded at the University of Texas/National Aeronautics and Space Administration (UT/NASA) seismic array: The University of Texas, Marine Science Institute, Contribution 465, Galveston Geophysics Laboratory, 27 pp.
- Jaksha, L. H., and Locke, J., 1981, Seismicity near Albuquerque, New Mexico, 1976-1978: U. S. Geological Survey, Open-File Report 81-117, 21 pp.
- Sanford, A. R., Olsen, K. H., and Jaksha, L. H., 1979, Seismicity of the Rio Grande Rift, in Riecker, R. E., ed., Rio Grande Rift; tectonics and magmatism: American Geophysical Union, Washington, D.C., p. 145-168.
- Sanford, A. R., Olsen, K. H., and Jaksha, L. H., 1981, Earthquakes in New Mexico, 1849-1977: New Mexico Bureau of Mines and Mineral Resources, Circular 171, 20 pp.
- Sanford, A. R., Mott, R. P. Jr., Shuleski, P. J., Rinehart, E. J., Caravella, F. J., Ward, R. M., and Wallace, T. C., 1977, Geophysical evidence for a magma body in the crust in the vicinity of Socorro, New Mexico, in Heacock, J. G., ed., The earth's crust: American Geophysical Union, Washington, D.C., Geophysical Monograph 20, p. 385-403.
- Sanford, A., Sandford, S., Wallace, T., Barrows, L., Sheldon, J., Ward, R., Johansen, S., and Merritt, L., 1980, Seismicity on the area of the waste isolation pilot plant (WIPP): Sandia National Laboratories, SAND80-7096, 74 pp.
- Wechsler, D. J., Cash, D. J., Olsen, K. H., McFarland, N. J., and Wolff, J. J., 1980a, Earthquake catalog for northern New Mexico, September 1973 - December 1979: Los Alamos Scientific Laboratory, Progress Report LA-8579-PR, 35 pp.
- Wechsler, D. J., Cash, D. J., Olsen, K. H., McFarland, N. J., and Wolff, J. J., 1980b, Earthquake catalog for northern New Mexico, January 1980 - March 1980: Los Alamos Scientific Laboratory, Progress Report LA-8580-PR, 12 pp.
- Wechsler, D. J., Cash, D. J., Olsen, K. H., McFarland, N. J., and Wolff, J. J., 1980c, Earthquake catalog for northern New Mexico, April-June 1980: Los Alamos Scientific Laboratory, Progress Report LA-8614-PR, 13 pp.
- Wechsler, D. J., Cash, D. J., Olsen, K. H., McFarland, N. J., and Wolff, J. J., 1981a, Earthquake catalog for northern New Mexico, July-September 1980: Los Alamos Scientific Laboratory, Progress Report LA-8687-PR, 13 pp.

Wechsler, D. J., Cash, D. J., Olsen, K. H., McFarland, N. J., and Wolff, J. J., 1981b, Earthquake catalog for northern New Mexico, October-December 1980: Los Alamos Scientific Laboratory, Progress Report LA-8745-PR, 16 pp.

Chapter 4

Lineament Map of the State of New Mexico*

Introduction

Ninety-one Landsat images were interpreted to produce a 1:500,000 scale lineament map of the state of New Mexico. This lineament map was then interpreted with the aid of published literature and available maps of gravity anomalies, temperature, Quaternary faults, geology, tectonics, and seismicity. Following the model of Chapin and Cather (1981), a Cenozoic plate tectonic history of New Mexico was developed. A time-series of four tectonic maps of New Mexico was constructed to illustrate the plate tectonic evolution of New Mexico from the Paleocene Epoch to the present. The significance of the lineament map and the plate tectonic model to geothermal exploration was analyzed.

Research Methodology

Satellite Data

Twenty multispectral scanner (MSS) images at 1:500,000 scale (i.e., 14" x 14" or approximately 112 x 112 miles) and 71 return-beam vidicon (RBV) images at 1:500,000 scale (i.e., 8" x 8" or approximately 64 x 64 miles) were used. The Band 6 MSS images, acquired by reflected sunlight filtered to 0.7 to 0.8 microns, were photographically enhanced at a commercial laboratory. The prints were dodged to keep all parts of each scene within the brightness range of the high contrast film and each scene was scale-matched to fit a base map

*The principal author of Chapter 4 is Dr. Larry Lepley, Consulting Geologist, Tucson, Arizona.

published by the U.S. Geological Survey. The RBV images were used to take advantage of the higher spatial resolution of the RBV camera, which is more than twice as fine as that of the MSS instrument (i.e., 30 meter as compared to 80 meter pixel sizes). The RBV images were taken by two panchromatic vidicon cameras that cover about one-fourth of the ground area per scene as do the MSS images. Standard RBV images with no enhancement were used but the photographic quality is highly variable. The center-point latitude and longitude is printed on each satellite image for indexing purposes.

Analysis and Synthesis

In the photointerpretation of the satellite scenes, the MSS and RBV images were analyzed separately and in stereoscopic combination of MSS with RBV. The stereoscopic MSS-RBV sets were the most effective for geologic interpretation. Those photolineaments that clearly cut Quaternary material were especially sought out and are indicated by broader lines on the lineament map. Folds are marked using the European symbology of arrowheads without the shafts. Arcuate and circular features that might be parts of calderas or domes are shown as dotted lines.

Because tectonic plate boundaries may be important target zones for geothermal exploration, a Cenozoic plate tectonic scenario was developed. A series of four plate-tectonic snapshots that show the evolution of the Rio Grande Rift during Paleocene, Eocene, Miocene, and Pliocene-Quaternary time was synthesized. This time history not only explains the possible origin of many of the satellite photolineament systems, but provides a model that accounts for certain patterns of distribution of volcanic centers, subsurface temperature anomalies, Quaternary faults, and gravity anomalies.

In the analysis of the lineament map, a geologic map of New Mexico (Dana and Backman 1965), a residual Bouguer gravity anomaly map of New Mexico (Aiken

et al. 1978), and Pliocene-Pleistocene and late Quaternary fault maps (Seager and Morgan 1979; Seager et al. 1981) were relied on heavily. The synthesis of these data was based mostly on recent literature of three kinds: (1) plate tectonics of western North America, (2) the dynamics of wrench faults, and (3) the evolution of the Rio Grande Rift. For the palinspastic reconstruction of the plate positions during the four time intervals, the lineament and geologic maps were cut and reassembled to obtain the best fit.

Background and Literature

There is a strong relationship between satellite photolineaments, geophysical lineaments, and zones of structural weakness and higher permeability that control the location and movement of geothermal fluids (Lepley and Doss 1975). Experience in geothermal exploration has shown that geothermal reservoirs tend to occur at transform faults. These microplate boundaries are marked by the coincidence of satellite photolineaments and alignments of geophysical (i.e., gravity and magnetic) anomalies.

At the New Mexico-Arizona border region, certain swarms of geophysical and satellite lineaments seem to extend into New Mexico (Lepley 1977, 1978, 1979). In the south, the NW-SE Texas-type of lineaments extend S45°E into New Mexico. Somewhat south of the Springerville volcanic field, a lineament swarm extends N45°E to N60°E over the state border. A series of east-west bundles of lineaments extends east at 32°, 33°20', and between 34° and 35° N latitude.

The northeast-southwest alignment of late-Cenozoic volcanism along the Jemez zone from Arizona through the Jemez volcano into Colorado was interpreted by Laughlin et al. (1976) as a linear rupture that has leaked magmas. Muehlberger (1978) suggests that the Frontal fault zone, a left lateral transform shear zone cutting NE-SW near Taos, extends southwest into

the Jemez zone. Baldrige (1979) believes that the Jemez zone is a transverse shear zone that taps a sub-crustal diapir. Chapin et al. (1978; Figure 1) identify several NW and NE lineaments, including the Jemez Lineament.

Two relevant papers from the Geological Society of America Bulletin are those of Cordell (1978) and Ramberg et al. (1978). Cordell (1978) deduced anomalous crustal structure along the axis of the rift from high heat flow, high elevation, high electrical conductivity, and gravity anomalies. The present rift follows the axis of Laramide, Pennsylvanian, and possibly earlier uplifts. Alignments of gravity gradients and magnetic lineaments show a gridded or en echelon NW and NE basement structural grain. The major faults of the rift system delineated by gravity gradients commonly do not follow the trend of smaller faults mapped at the surface. Ramberg et al. (1978) stripped away the gravity effect of the basin sediments and showed that a +30 mgal anomaly remains under the rift.

The American Geophysical Union collection of papers on the Rio Grande Rift edited by Riecker (1979) was useful in interpreting the Landsat photolineaments. Some pertinent papers in this collection are reviewed briefly here.

Sanford et al. (1979) noted that a seismic zone extends NE-SW through Mt. Taylor (the Jemez Lineament?).

Swanberg (1979) used high heat flow anomalies to define the Rio Grande Rift as distinct from the basin-and-range block faulting. The rift zone thus defined extends from Presidio, Texas, to Central Colorado.

Gries (1979) explained that one difficulty in tracing the rift into Chihuahua is caused by the plastic flow of anomalously hot evaporites in the basins that may show no Cenozoic scarps. Seager and Morgan (1979) delineated the rift zones by high heat flow, great depth of basins, and Quaternary

faulting to show that the rift extends 100 to 200 miles into west Texas and Sonora. According to Seager and Morgan (1979), basin-and-range faulting began at 21 m.y. (Miocene), the upper mantle bulge began to produce alkali-olivine basalts at 13 m.y., and peak rifting occurred at 5 m.y.

A model of the plate tectonic history of the western United States shows the Rio Grande Rift opening in NE-SW direction from 30 to 10 m.y. while the Eastern Snake River Plain was a transform zone (Eaton 1979). After 7 m.y., the Eastern Snake River Plain has been a spreading center and the Rio Grande Rift is opening WNW-ESE. Modern transform zones include the Texas Lineament system, Walker Lane, and a system extending NW from Colorado.

Lipman (1981) also proposed a clockwise switch from NE to NW spreading of the Rio Grande Rift. Lipman (1981) dates the switch at 10 m.y.

Chapin et al. (1978) defined lineaments as deeply penetrating flaws in the lithosphere that tend to leak magma and to influence deformation in the brittle near-surface rock. Deflections of regional lineaments to measure the extent of spreading of the Rio Grande Rift were used in the initial work of Chapin et al. (1978). Chapin and Cather (1981) completely revised the earlier tectonic model. Based, in part, on the existence of drag structures and displaced carbonatite provinces, a 120-km Laramide San Andreas-type right lateral wrench fault offset along the axis of the present Rio Grande Rift was proposed. The Chapin and Cather (1981) model was adopted for the Paleocene-Eocene reconstruction of New Mexico plate positions.

New developments in the understanding of wrench fault tectonics has made regional lateral faults easier to recognize in satellite images. For example, Freund (1974) published a comprehensive study of wrench faults with model studies and actual faults; Tchalenko (1970) conducted laboratory experiments on shear zones of different magnitudes; Davidson (1980) applied these types

of results to petroleum exploration; and Peterson (1979) applied wrench fault theory to interpretation of Landsat images.

Lineament Map New Mexico

Figures 4-1 and 4-2 are lineament maps of New Mexico originally drafted at a scale of 1:500,000. The lineaments include a variety of earth ruptures or lithospheric flaws. These include faults, fracture zones, and jointing systems. Prominent lineaments that cross Pleistocene or younger formations were labeled as probably Quaternary faults. Other features on the lineament map are folds, domes, and circular features. Circular features were mapped if they appeared to have an igneous origin.

The lineament systems correlate well with alignments of gravity anomaly patterns in the residual Bouguer gravity map by Aiken et al. (1978). This correlation indicates the deep origin of the satellite photolineaments. For regional geothermal assessment, the lineament maps are best used as overlay sheets with complementary data such as a gravity map (Aiken et al. 1978), maps of Pliocene and Quaternary faults (Seager and Morgan 1979; Seager et al. 1981), and maps of thermal anomalies (Lohse 1981, in preparation).

Tectonic Interpretation of the Lineament Map

The dynamic model of Cenozoic plate tectonic history was synthesized so that the lineament map could be interpreted in terms of active or inactive plate boundaries, the location of transform fault zones, and the targeting of zones for regional geothermal exploration. The tectonic model is summarized by the four sequence maps (see Figures 4-3 through 4-6) showing plate

- EXPLANATION**
- FAULTS, FRACTURE ZONES, AND OTHER LINEAR EARTH RUPTURES
 - RELATIVE MOTION SHOWN BY ARROWS; SALL ON THE DOWNTROW SIDE OF FAULT
 - QUATERNARY FAULT
 - CIRCULAR FEATURES INCLUDING RING DISES, RING FRACTURES, VOLCANIC MONTS, AND CALDERAS
 - CURVILINEAR FEATURES INCLUDING MONOCLINES AND LIMBS OF FOLDS
 - DIKE
 - ANTICLINE
 - SYNCLINE
 - MONOCLINE
 - DOME

Figure 4-1. A lineament map of northern New Mexico.

- EXPLANATION**
- FAULTS, FRACTURE ZONES, AND OTHER LINEAR EARTH RUPTURES
 - RELATIVE MOTION SHOWN BY ARROWS, BALL ON THE DOWNTROW SIDE OF FAULT
 - QUATERNARY FAULT
 - CIRCULAR FEATURES INCLUDING RING DICES, RING FRACTURES, VOLCANIC MOUNTS, AND CALDERAS
 - CURVILINEAR FEATURES INCLUDING MONOCLINES AND LIMBS OF FOLDS
 - DIKE
 - ANTICLINE
 - SYNCLINE
 - MONOCLINE
 - DOVE

Figure 4-2. A lineament map of southern New Mexico.

Figure 4-4. Plate configurations in western New Mexico during the Eocene Epoch.

Figure 4-6. Plate configurations in western New Mexico during Pliocene-Quaternary time.

configurations during Paleocene, Eocene, Miocene, and Pliocene-Quaternary time, respectively.

The tectonic maps were produced by first determining the locations of plate boundaries and then determining the sense and time of plate movement along those boundaries. Plate boundaries were drawn at the maximum coincidence of known faults with gravity lineaments, alignments of volcanic centers, thermal anomalies, and Landsat photolineament systems. Sense of lateral motion was determined by the arrangement of en echelon drag folds and conjugate shear fault systems.

The time and sequence of plate movement were taken from Eaton (1979), Lipman (1981), and Chapin and Cather (1981). The most radical part of the model, adopted from Chapin and Cather (1981), is the 60 to 120 km right-lateral compressional wrench fault along the axis of the present Rio Grande Rift during Paleocene and Eocene time. This hypothesis is borne out by at least four lines of evidence: (1) Laramide stress vectors; (2) telescoping of the northern edge of the Colorado Plateau; (3) wrench fault tectonics; and (4) offset of lineament systems and geologic formations.

The northeast-directed Paleocene-Eocene stress was directed north 45° E such that the first order wrench direction was nearly parallel with the trend of the southern Rocky Mountains. The area north of the Colorado Plateau was strongly telescoped as a result of the NNE movement of the plateau along the wrench fault.

Curved anastomosing faults, side stepping faults, and drag folds are pervasive in pre-Miocene rocks at the borders of the Rio Grande Rift. Right lateral wrench fault tectonic patterns of the type described by Peterson (1979), Davidson (1980), Freund (1974), and Tchalenko (1970) are evident in the Landsat images. The arcuate north to northeast lineaments and folds on the lineament map and faults and drag folds in the tectonic map (Woodward et

al. 1978) should be noted. Chapin and Cather (1981) cite carbonatite-bearing granites near Socorro as a possible offset counterpart of the granite with carbonatite in the Caballo Mountains 120 km to the south on the opposite side of the rift.

Paleocene Epoch

In order to generate the Paleocene configurations, the lineament maps and the geologic map of New Mexico were cut and the pieces displaced 130 kilometers left-laterally along the axis of the present rift to the pre-wrench position. This restoration caused certain lineament systems to be aligned across that wrench (see Figure 4-3). The NW-SE sets are considered to be antithetic faults, following the nomenclature used by Chapin and Cather (1981), borne at the time of inception of the NNE synthetic faults along which the major lateral movement took place. For future reference, three of the antithetic faults were named after the geographic locations that they traverse (i.e., Vallecitos-Vaughn, Socorro-Caballo, and Mangas-Ahumada). Two of the ENE lineament swarms that are aligned in the plate reconstruction were also named the San Augustin-Jicarilla Lineament and Santa Rita-Pinon Lineament.

Eocene Epoch

In late Paleocene-early Eocene, maximum viscous coupling of the plateau with the shallow-dipping Farallon Plate and a shift in the axis of compression from ENE to NE caused rapid movement along the Rio Grande synthetic fault. In Figure 4-4, the wrench faulting is shown as complete, and the remaining distortion of the state boundary compensates for the later opening of the rift. The apparent continuation of the Socorro-Caballo lineament system across the Rio Grande wrench fault may be only fortuitous.

Miocene Epoch

In the plate tectonic model of the western United States of Eaton 1979, the Eastern Snake River Plain was a transform fault zone and spreading was WSW-ENE in Miocene time. According to Lipman (1981), back-arc extension was WSW to ENE at that time. Both of these models support the SW-NE extension of the Rio Grande Rift shown in Figure 4-5. Some of the northeasterly transform zones along which the plates moved away from the rift (or rifts) may have been synthetic wrench faults during the Paleocene and Eocene epochs.

The Vaughn Plate moved northeast away from the Tularosa Rift, buckling the crust of eastern New Mexico into folds at its front, and leaving the Jornada Block behind. These folds were shown as Pliocene-Quaternary folds on the fault maps by Seager and Morgan (1979). Southwesterly-extending basin-and-range spreading was active during the Miocene Epoch. In Figure 4-5, the action of all the individual fault blocks in southwestern New Mexico is not shown in detail; however, the basin-and-range spreading is depicted schematically. The Datil Block moved away from the Palomas Rift as a unit, while sliding along the right-lateral San Augustin transform zone. The Jemez transform zone was active and may have extended as far southwest as Mt. Taylor. Valles Caldera of the Jemez volcanics and Mt. Taylor Volcano are shown as dotted circles in Figure 4-5.

Pliocene-Quaternary Time

According to the model of Lipman (1981), the WSW-ESE back-arc extension rotated 45° counter-clockwise to WNW-ESE at 10 m.y. and has persisted to the present. In the model of Eaton (1979), the Eastern Snake River Plain shifted to becoming a spreading center opening NW-SE and the Rio Grande Rift has been opening WNW-ESE since 7 m.y. before present. Figure 4-6 reflects that model,

showing the Rio Grande Rift opening NW-SE along NW-SE transform zones that were once Paleocene antithetic wrench fault zones.

The Mangas Trench is a transform fault system with probable right lateral movement. The Jornada transform shear zone transects the Jornada Block and extends from the Palomas Rift to the Tularosa Rift. The Socorro transform system is another reactivated Paleocene antithetic wrench fault system. The Vallecitos transform system may extend northwest to the Nevada end of the Eastern Snake River Rift, as given in the model by Eaton (1979). Circular igneous features prominent on Landsat images that are also centered in gravity low anomalies are shown on Figure 4-6. These areas are targets of interest to geothermal exploration because some of them may represent magma chambers.

Discussion

The Jemez Zone

Laughlin et al. (1976) noted that volcanoes of the Colorado Plateau trend along a NE-SW line through the Jemez Volcano from southeastern Colorado through New Mexico into Arizona. In this study, no single N45°E lineament connecting these volcanic centers was identified. Instead, the volcanoes appear to be controlled by a network of N30°E and N60°E lineaments. Some of the N30°E lineaments may have been right lateral synthetic wrench faults active during the Paleocene Epoch. Many of the N60°E lineaments may have been transform fault zones related to the NE-SW opening of the Rio Grande Rift in Miocene time. These preexisting zones of weakness are not conduits for magmas. The general N45°E trend of the entire volcanic system could mean that a subcrustal zone of that orientation lies at deeper levels and does not directly penetrate to the surface, but instead supplies magma to the preexisting overlying fault network.

The Pliocene Quaternary Transform Zones

The Plateau Plate may be moving more rapidly northwest from the Rio Grande Rift zone than the adjacent parts of the Colorado Plateau. The transform boundaries of the Plateau Plate are the Vallecitos transform and the Socorro transform (see Figure 4-6).

The N45°W Vallecitos right-lateral transform system begins at the south end of the San Luis Rift Valley, cuts through the San Juan volcanics of Colorado, and may continue through Utah and Nevada to the southwestern end of the Eastern Snake River Rift (Eaton 1979; Figure 7). Mamby Hot Springs lies at the intersection of Vallecitos transform with the Rio Grande Rift. Other more minor northwesterly transform zones extend into the Plateau Plate through the Baca Location #1 KGRA, through the San Ysidro KGRA, and through Mt. Taylor.

The Socorro transform system includes the Socorro Peak KGRA and extends about 200 kilometers to either side of the Rio Grande Rift. The present Socorro transform zone follows Paleocene antithetic wrench fault systems.

The Jornada transform zone also follows Paleocene wrench fault systems. The Jornada Basin, the Radium Springs KGRA, the Organ Pipe Caldera, and Hueco tank wells are in this transform zone. The Gila Hot Springs KGRA may be located on a northwesterly extension of the Jornada transform.

The Mangas Trench marks the northern edge of a right-lateral transform system that is hundreds of kilometers wide and extends a thousand kilometers northwest to the California-Nevada border (Eaton 1979). The Mangas transform system extends through a region that has been shattered and softened by basin-and-range spreading. This system contains the Kilbourne Hole KGRA and the Faywood Hot Springs area.

The Lower Frisco Hot Springs KGRA and the Lightning Dock KGRA are located on strands of north-south Paleocene wrench faults. These faults are being forced open by block rotation driven by the right-lateral shear of the Mangas transform zone.

A comparison of the Geothermal Resources of New Mexico map (Swanberg 1980) with Figure 4-6 shows that most of the larger KGRA's are at the intersection of the Rio Grande Rift and the NW-SE transform zones. These KGRA's include Kilbourne Hole, Radium Springs, Socorro Peak, San Ysidro, and Baca. The intersection of the Vallecitos transform and the Rio Grande Rift should be considered as a geothermal exploration target zone. Other exploration targets should include those areas enclosed by circles in Figure 4-6. These areas represent circular or arcuate features visible on the Landsat images that coincide with gravity lows shown on the map by Aiken et al. (1978).

References

- Aiken, C. L. V., Laughlin, A. W., and West, F. G., 1978, Residual Bouguer gravity anomaly map of New Mexico: Los Alamos National Laboratory, scale 1:500,000.
- Baldrige, W. S., 1979, Petrology and photogenesis of Plio-Pleistocene basaltic rocks from the central Rio Grande Rift, New Mexico, and their relation to the rift structure, in Riecker, R. E., ed., Rio Grande Rift, tectonics and magmatism: American Geophysical Union, Washington, D.C., p. 323-354.
- Chapin, C. E., and Cather, S. M., 1981, Eocene tectonics and sedimentation in the Colorado Plateau, Rocky Mountain area, in Dickenson, W. R., and Payne, W. D., eds., Relations of tectonics to ore deposits in the southern cordillera: Arizona Geological Society, Digest, v. 14, p. 173-198.
- Chapin, C. E., Elston, W. E., and James, H. L., eds., 1978, Field guide to selected cauldrons and mining districts of the Datil-Mogollon volcanic field, New Mexico: New Mexico Geological Society, Special Publication 7, 149 pp.
- Cordell, L., 1978, Regional geophysical setting of the Rio Grande Rift: Geological Society of America, Bulletin, v. 89, p. 1073-1090.
- Dana, C. H., and Backman, G. O., 1965, Geologic map of New Mexico: U. S. Geological Survey, scale 1:500,000.
- Davidson, J. K., 1980, Rotational displacements in southeastern Australia and their influence on hydrocarbon occurrence: Tectonophysics, v. 63, p. 139-153.
- Eaton, G. P., 1979, A plate-tectonic model for late Cenozoic crustal spreading in the western United States, in Riecker, R. E., ed., Rio Grande Rift, tectonics and magmatism: American Geophysical Union, Washington, D. C., p. 7-32.
- Freund, R., 1974, Kinematics of transform and transcurrent faults: Tectonophysics, v. 21, p. 135-164.
- Gries, J. C., 1979, Problems of delineation of the Rio Grande Rift into the Chihuahua tectonic belt of northern Mexico, in Riecker, R. E., ed., Rio Grande Rift, tectonics and magmatism: American Geophysical Union, Washington, D.C., p. 107-114.
- Laughlin, A. W., Brookins, D. G., and Damon, P. E., 1976, Late-Cenozoic basaltic volcanism along the Jemez zone of New Mexico and Colorado (abs.): Geological Society of America, 2nd Annual Rocky Mountain Meeting, Proceedings, p. 598.

- Lepley, L. K., 1977, Landsat lineament map of Arizona with emphasis on Quaternary fractures: Geothermal Group, Arizona Bureau of Geology and Mineral Technology, scale 1:100,000.
- Lepley, L. K., 1978, Geophysical lineaments of Arizona: Los Alamos National Laboratory, Technical Report, 41 pp.
- Lepley, L. K., 1979, Skylab lineament map of Arizona with tectonic model and exploration guide for geothermal resources, in Hahman, W. R., ed., Geothermal reservoir site evaluation in Arizona: Geothermal Group, Arizona Bureau of Geology and Mineral Technology, scale 1:500,000.
- Lepley, L. K., and Doss, A. K., 1975, The use of earth resources technology satellite aeromagnetic, gravity, and thermal data for mapping potential geothermal resources (abs.): American Association of Petroleum Geologists, Rocky Mountain Section, 24th Annual Meeting, Albuquerque, Proceedings.
- Lipman, P. W., 1981, Volcano-tectonic setting of Tertiary ore deposits, southern Rocky Mountains, in Dickinson, W. R., and Payen, W. D., eds., Relations of tectonics to ore deposits in the southern cordillera: Arizona Geological Society, Digest, v. 14, p. 199-213.
- Lohse, R. L., 1981, Temperature studies in southwestern New Mexico, in Icerman, L., and Starkey, A., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1981: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 7/35 - 7/82 (In Press).
- Lohse, R. L., Morgan, P., and Swanberg, C. A., 1981, A heat-flow study of Dona Ana County, southern Rio Grande Rift, New Mexico, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program fiscal year 1980: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 5/1 - 5/40.
- Muehlberger, W. R., 1978, Frontal fault zone of northern Picuris range, in Hawley, J. W., ed., Guidebook to Rio Grande Rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources, Circular 163, p. 44-46.
- Peterson, R., 1979, Oil and gas exploration by pattern recognition of lineament assemblages associated with bends in wrench faults: Environmental Remote Sensing Institute of Michigan, 13th International Symposium on Remote Sensing Institute of the Environment, Ann Arbor, Proceedings, v. 2, p. 23-27.
- Ramberg, I. B., Cook, F. A., and Smithson, S. B., 1978, Structure of the Rio Grande Rift in southern New Mexico and west Texas based on gravity interpretations: Geological Society of America, Bulletin, v. 89, no. 1, p. 107-123.

- Riecker, R. E., ed., 1979, Rio Grande Rift, tectonics and magmatism: American Geophysical Union, Washington, D.C., 438 pp.
- Sanford, A. R., Olsen, K. H., and Jaksha, L. H., 1979, Seismicity of the Rio Grande Rift, in Riecker, R. E., ed., Rio Grande Rift, tectonics and magmatism: American Geophysical Union, Washington, D.C., p. 145-168.
- Seager, W. R., and Morgan, P., 1979, The Rio Grande Rift in southern New Mexico, west Texas, and northern Chihuahua, in Riecker, R. E., ed., Rio Grande Rift, tectonics and magmatism: American Geophysical Union, Washington, D.C., p. 87-106.
- Seager, W. R., Shafiquallah, M., and Clemons, R. E., 1981, Active fault analysis and radiometric dating of young basalts in southern New Mexico, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1980: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 6/1 - 6/12.
- Swanberg, C. A., 1979, Chemistry of thermal and non-thermal groundwaters in the Rio Grande Rift and adjacent tectonic provinces, in Riecker, R. E., ed., Rio Grande Rift, tectonics and magmatism: American Geophysical Union, Washington, D.C., p. 279-288.
- Swanberg, C. A., compiler, 1980, Geothermal resources of New Mexico: New Mexico Energy Institute at New Mexico State University, map, scale 1:500,000.
- Tchalenko, I. S., 1970, Similarities between shear zones of different magnitudes: Geological Society of America, Bulletin, v. 81, p. 1625-1640.
- Woodward, L. A., Callender, J. F., Seager, W. R., Chapin, C. E., Gries, J. C., Shaffer, W. L., and Zilinski, R. E., 1978, Tectonic map of Rio Grande Rift region in New Mexico, Chihuahua, and Texas, in Hawley, J. W., ed., Guidebook to Rio Grande Rift in New Mexico and Colorado, New Mexico Bureau of Mines and Mineral Resources, Circular 163, scale 1:1,000,000.

Chapter 5

Collection of Existing Water Well Data in the Southern Rio Grande Rift and Southwestern New Mexico*

Introduction

In order to identify existing water wells suitable for temperature logging in southwestern New Mexico, 98 well sites were located by topographic map inspection and field reconnaissance in the counties of Dona Ana (see Figure 5-1 and Table 5-1), Grant (see Figure 5-2 and Table 5-2), Hidalgo (see Figure 5-3 and Table 5-3), Luna (see Figure 5-4 and Table 5-4), and Sierra (see Figure 5-5 and Table 5-5). During the fall of 1980 and the spring of 1981, each site was visited to identify those wells that could be logged. Of the 98 well sites, 59 were found to be operating wells which were closed and could not be logged, 16 were abandoned but not suitable for temperature logging, nine were suitable for logging but not immediately accessible, 13 were logged, and one flowing well was measured for water temperature.

The 16 abandoned wells not suitable for temperature logging had pipes or pumps left in the well, or had broken casings or cave-ins. The high probability of losing the temperature-logging cable and probe prohibits the use of this equipment in potentially hazardous wells of this type.

*The principal author of Chapter 5 is Richard L. Lohse, Geothermal Field Engineer, New Mexico Energy Institute at New Mexico State University.

Figure 5-1. Locations of wells examined for temperature logging in Dona Ana County.

Table 5-1. Wells examined for temperature logging in Dona Ana County.

<u>Latitude</u>	<u>Longitude</u>	<u>Well Number</u>	<u>Remarks</u>
32°18.4'	106°52.0'	1	Logged
32°18.0'	106°44.4'	2	Logged
32°06.5'	106°38.5'	3	Logged
32°06.4'	106°38.5'	4	Logged

Figure 5-2. Locations of wells examined for temperature logging in Grant County.

Table 5-2. Wells examined for temperature logging in Grant County.

<u>Latitude</u>	<u>Longitude</u>	<u>Well Number</u>	<u>Remarks*</u>
32°35.5'	108°03.9'	5	No access
32°35.3'	108°08.0'	6	No access
32°35.3'	108°07.1'	7	Logged
32°34.8'	108°08.6'	8	Running, no access
32°34.8'	108°07.6'	9	Logged
32°33.8'	108°10.4'	10	Running, no access
32°32.5'	108°08.9'	11	Can be logged
32°31.5'	108°11.0'	12	Running, no access
31°55.0'	108°25.6'	13	Running, no access
31°54.8'	108°29.5'	14	Running, no access
31°54.5'	108°19.2'	15	Running, no access
31°53.3'	108°27.7'	16	Running, no access
31°53.3'	108°29.5'	17	Running, no access
31°52.5'	108°16.6'	18	Logged

*The "can be logged" description refers to wells that were located in the field and appeared to be in a condition that would allow temperature logging equipment to be utilized safely. These wells were not logged for various reasons, including the lack of physical access to the immediate area, the inability to obtain permission from the owner to disturb the wellhead configuration, the lack of proper equipment to open the well, and equipment malfunction.

Figure 5-3. Locations of wells examined for temperature logging in Hidalgo County.

Table 5-3. Wells examined for temperature logging in Hidalgo County.

<u>Latitude</u>	<u>Longitude</u>	<u>Well Number</u>	<u>Remarks</u>
31°51.6'	108°15.5'	19	Running, no access
31°51.5'	108°25.6'	20	No access
31°51.3'	108°21.5'	21	Running, no access
31°49.3'	108°17.0'	22	Running, no access
31°49.0'	108°21.5'	23	Running, no access
31°48.3'	108°16.1'	24	Running, no access
31°46.0'	108°23.1'	25	Running, no access
31°42.8'	108°19.2'	26	Running, no access
31°42.0'	108°22.1'	27	Running, no access
31°40.4'	108°17.3'	28	Running, no access
31°39.7'	108°16.0'	29	Running, no access
31°38.6'	108°13.7'	30	Running, no access
31°38.3'	108°20.6'	31	Running, no access
31°37.7'	108°16.7'	32	Running, no access
31°37.0'	108°12.6'	33	Running, no access
31°35.7'	108°15.0'	34	Running, no access
31°34.9'	108°17.0'	35	Running, no access
31°34.9'	108°14.5'	36	Running, no access
31°34.4'	108°13.4'	37	Running, no access
31°30.0'	108°14.4'	38	Logged

Figure 5-4. Locations of wells examined for temperature logging in Luna County.

Table 5-4. Wells examined for temperature logging in Luna County.

<u>Latitude</u>	<u>Longitude</u>	<u>Well Number</u>	<u>Remarks*</u>
32°35.4'	107°27.5'	39	Running, no access
32°33.4'	107°46.9'	40	Can be logged
32°33.0'	107°54.4'	41	Access questionable
32°32.5'	107°22.2'	42	Can be logged
32°32.4'	107°47.4'	43	Running, no access
32°32.1'	107°49.6'	44	Can be logged
32°31.9'	107°51.7'	45	Running, no access
32°30.5'	107°24.0'	46	No access
32°29.8'	107°46.5'	47	Can be logged
32°29.4'	108°05.5'	48	Running, no access
32°29.3'	107°51.8'	49	Can be logged
32°29.0'	107°22.6'	50	Logged
32°28.9'	107°42.0'	51	Running, no access
32°28.7'	108°11.5'	52	Running, no access
32°28.5'	107°57.0'	53	Running, no access
32°28.5'	107°46.0'	54	Running, no access
32°28.2'	107°53.1'	55	Can be logged
32°28.2'	107°22.7'	56	Running, no access
32°28.1'	107°54.9'	57	Running, no access
32°27.3'	107°29.5'	58	Can be logged
32°26.8'	108°06.3'	59	Running, no access
32°26.7'	107°26.2'	60	Running, no access
32°26.5'	107°54.6'	61	Running, no access
32°25.8'	107°41.7'	62	Running, no access
32°25.3'	107°32.3'	63	Running, no access
32°25.0'	107°54.6'	64	No access, padlocked
32°24.9'	107°52.0'	65	Running, no access
32°24.5'	107°55.7'	66	No access
32°23.9'	107°54.0'	67	No access
32°22.5'	107°51.6'	68	Running, no access
32°21.5'	107°47.1'	69	Running, no access
32°21.2'	107°41.9'	70	Running, no access
32°19.5'	107°38.0'	71	Running, no access
32°17.8'	107°40.4'	72	No access, padlocked
32°15.4'	107°27.5'	73	Logged
32°13.2'	107°25.8'	74	Running, no access
32°12.1'	107°35.0'	75	No access, 30 ft. mine
32°10.2'	107°35.9'	76	Can be logged
32°09.4'	107°35.5'	77	Running, no access
32°08.4'	107°35.3'	78	No access
32°07.0'	107°35.3'	79	Running, no access
32°05.5'	107°35.5'	80	Running, no access
32°03.0'	107°34.6'	81	Running, no access
32°01.6'	107°36.4'	82	Running, no access
32°01.0'	107°40.0'	83	Running, no access

*The "can be logged" description refers to wells that were located in the field and appeared to be in a condition that would allow temperature logging equipment to be utilized safely. These wells were not logged for various reasons, including the lack of physical access to the immediate area, the inability to obtain permission from the owner to disturb the wellhead configuration, the lack of proper equipment to open the well, and equipment malfunction.

Figure 5-5. Locations of wells examined for temperature logging in Sierra County.

Table 5-5. Wells examined for temperature logging in Sierra County.

<u>Latitude</u>	<u>Longitude</u>	<u>Well Number</u>	<u>Remarks</u>
33°08.0'	107°14.4'	84	Logged
32°56.3'	107°27.2'	85	Logged
32°55.5'	107°31.3'	86	Running, no access
32°55.3'	107°33.6'	87	Running, no access
32°53.5'	107°32.8'	88	No access, padlocked
32°44.5'	107°32.2'	89	Logged
32°44.5'	107°32.2'	90	Flowing, temperature measurement only
32°43.5'	107°34.5'	91	Running, no access
32°42.2'	107°30.5'	92	No access, capped with rocks
32°42.0'	107°33.6'	93	Running, no access
32°41.5'	107°26.4'	94	No access
32°41.1'	107°27.3'	95	Running, no access
32°41.1'	107°27.3'	96	No access, capped with cement
32°37.0'	107°27.7'	97	No access
32°36.5'	107°30.3'	98	Running, no access

Discussion

The measured temperature-depth data for the 13 wells that were logged are presented in Table 5-6. Temperature-depth profiles of these wells are shown in Figures 5-6 and 5-7. Eleven of the wells are cool. These cool temperatures are believed to be the result of groundwater recharge and lateral groundwater flow. In addition, the nature of the wells themselves (e.g., water wells are deliberately drilled in areas suspect of having strong recharge, enhanced strata permeability, and groundwater flow), as well as the time of year most of the wells were logged (i.e., mostly during the winter months) may contribute to the likelihood of observing abnormally low temperatures. The fact that most of the wells are shallow (i.e., less than 50 meters) enhances the probability that local groundwater disturbances had an influence on the temperature-depth data. A few of the wells have cool temperatures and high temperature gradients. The latter observation is probably due to the recovery of temperatures with depth as groundwater disturbances become insignificant.

Three of the wells appear to be anomalous. Two of these wells are in areas already known to have some geothermal potential. The warmest well, Number 84, is in the immediate area of the hot springs in downtown Truth or Consequences and was drilled as a geothermal well. The second warmest well, Number 2, is located near the Las Cruces east mesa geothermal anomaly. This well was drilled by the City of Las Cruces as a potential water well. Like two of its predecessors, LC-1 and LC-2 with bottom-hole temperatures of 54°C and 68°C, respectively, the temperature of this well suggests that the geothermal anomaly under the Las Cruces east mesa is larger than first suspected.

Table 5-6. Measured temperature-depth data of the 13 wells logged in southwestern New Mexico.

County	Location		Well Number	Depth (meters)	Temperature (°C)
	Latitude	Longitude			
Dona Ana	32°18.4'	106°52.0'	1	15	16.5
				25	17.5
				95	19.6
				100	20.1
				105	20.9
				110	21.3
				115	21.7
				120	22.0
				125	22.3
				130	22.4
				135	22.5
Dona Ana	32°18.0'	106°44.4	2	61	27.2
				76	27.9
				91	28.8
				107	29.4
				122	29.7
				152	31.9
				183	30.9
				213	30.7
				244	31.8
				259	32.6
				274	33.6
				282	34.2
Dona Ana	32°06.5'	106°38.5'	3	15	18.6
				20	18.8
				25	18.9
				30	19.0
				35	19.0
				40	19.0
				42	19.5
Dona Ana	32°06.4'	106°38.5'	4	25	19.1
				30	19.2
				35	19.4
				40	19.8
				45	20.0
				50	20.3
				55	20.5

Table 5-6. (continued).

County	Location		Well Number	Depth (meters)	Temperature (°C)
	Latitude	Longitude			
Grant	32°35.3'	108°07.1'	7	5	13.7
				10	13.7
				15	13.8
				20	13.8
				25	13.9
				30	14.2
				35	14.3
				40	14.5
				45	14.7
				50	14.9
				55	14.9
				60	15.0
				65	15.0
Grant	32°34.8'	108°07.6'	9	5	13.1
				10	13.2
				15	13.2
				20	13.6
				25	13.8
				30	13.9
				35	14.2
				40	14.5
Grant	31°52.5'	108°16.6'	18	5	14.8
				10	15.4
				15	16.7
				20	16.7
				25	16.6
Hidalgo	31°30.0'	108°14.4'	38	5	16.0
				10	16.0
				15	16.2
				20	16.2
				25	16.2
				30	16.3
				35	16.4
				40	16.5
				45	16.6
				50	17.2
				55	17.1
				60	17.0
				65	17.2

Table 5-6. (continued).

County	Location		Well Number	Depth (meters)	Temperature (°C)
	Latitude	Longitude			
Luna	32°29.0'	107°22.6'	50	5	11.9
				10	12.3
				15	13.0
				20	12.9
Luna	32°15.4'	107°27.5'	73	5	11.9
				10	11.9
				15	12.8
				20	12.9
				25	13.0
				30	13.1
Sierra	33°08.0'	107°14.4'	84	5	33.2
				10	33.9
				15	34.5
				20	35.2
				25	35.8
				30	36.3
				35	36.6
				40	37.1
				45	37.7
				50	38.2
				55	38.7
				60	39.2
				62	39.4
Sierra	32°56.3'	107°27.2'	85	5	15.1
				10	15.0
				15	15.0
				20	15.1
				25	15.2
				30	15.3
				35	15.5
				40	15.5
				45	15.6
				47	15.7
Sierra	32°44.5'	107°32.2'	89	5	15.7
				10	17.5

Figure 5-6. Temperature-depth profiles for the wells logged with depths shallower than 70 meters. The identification numbers refer to well numbers given in Table 5-6.

Figure 5-7. Temperature-depth profiles for the wells logged with depths greater than 70 meters. The identification numbers refer to well numbers given in Table 5-6.

The temperature data for Well 2 are different than the temperature data from the other wells in that it was logged immediately after drilling (i.e., before the hole had time to equilibrate), which was the only time that the hole was available for temperature logging. The measured temperatures, which were actually mud temperatures, could be as much as 10°C less than the equilibrium values.

The third anomalous well, Number 90, is located in Sierra County (see Figure 5-5), which presently has no known geothermal anomalies. This well is flowing and has a measured temperature of 32.7°C. The production zone of this well is reportedly about 33.5 meters.

The three wells with the next highest temperatures are Wells 1, 3, and 4. Although these wells are not anomalous, all three are in Dona Ana County and, in particular, are located in the Mesilla Bolson not far from the faulted boundaries of the basin. Wells 3 and 4 are near the eastern boundary of the basin, which is controlled by the Mesilla Valley Fault. Well 1 is located near the western boundary of the basin, which is structurally controlled by the Robledo Fault. Both these faults are believed to act as conduits for the migration of hydrothermal fluids (Lohse et al. 1981). These three wells may be just outside the influence of these fault-controlled hydrothermal systems. Temperatures could increase at greater depths in these areas because the potential near-surface temperatures may be masked by lateral groundwater flows.

Detailed temperature gradients and heat-flow values are not presented for these wells because these data are believed to be heavily influenced by groundwater disturbances and not indicative of the local thermal regimes. The temperature gradients and heat-flow values are exceptionally high because of the recovery of temperatures from suppressed values as the influence of local groundwater disturbances diminish with depth.

Acknowledgements

The data reported for Well Number 2 were collected by Eddie Ferguson of the Physical Science Laboratory at New Mexico State University.

Reference

Lohse, R. L., Morgan, P. and Swanberg, C. A., 1981, A heat-flow study of Dona Ana County, southern Rio Grande Rift, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1980: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 5/1 - 5/40.

Chapter 6

Temperature Gradient, Resistivity, and Magnetic Surveying on the West Mesa of Albuquerque*

Introduction

The current geothermal studies in the Albuquerque area concentrated on the western side of the city (see Figure 6-1), which is an area of anticipated growth. The warmest municipal groundwater temperature (32°C in 360 m deep West Mesa #1 in Figure 6-1) was reported in this area by Bjorklund and Maxwell (1961). The 32°C temperature still represents the highest pumped temperature of a city water well despite many wells being drilled recently, some near the Albuquerque volcanoes (Figure 6-1).

The Albuquerque volcanoes shown in Figure 6-1 are a group of fissure-controlled basaltic volcanoes and spatter cones, which have been episodically active from about 200,000 to at least 120,000 years before present (Bachman et al. 1975; Machette 1978). These formations appear to be related to the Nine Mile (County Dump) Fault (see Figure 6-1) described by Kelley (1977) and Machette (1978), respectively. The only other mapped faults in the survey area are the unnamed faults on the west side of Figure 6-1 (Kelley 1977). Machette (1978) detailed 17 m of vertical displacement on the County Dump Fault (Nine Mile Fault) in the past 400,000 years and only 10 m or so of offset was discussed by Kelley (1977) on the faults to the west.

The escarpments on the east and west of Figure 6-1 bound the Ceja Mesa of

*The principal author of Chapter 6 is Dr. George R. Jiracek, Professor of Geological Sciences, Department of Geological Sciences, San Diego State University.

Kelley (1977) (also called the Llano de Albuquerque), which extends beyond the north-south confines of Figure 6-1 for a total length of 110 km. Parker and Jiracek (1980) have chosen the name Llano de Atrisco for the segment of the mesa encompassed in Figure 6-1. The northeastern portion of the Llano in Figure 6-1 is mantled by basaltic lava flows from the Albuquerque volcanoes. Scarps shown on the rest of the map are formed by resistant calichified soil of post-Santa Fe gravel and eolian sands. Underlying beds of youngest Santa Fe Group sands and gravel are exposed on the erosional scarps. An oil test well (Carpenter #1 Atrisco), drilled in 1948 just north of U.S. Highway 66 (see Figure 6-1) in Sec. 28.440, T. 10 N., R. 1 E., reached a depth of 2027 m before leaving the Santa Fe. Bjorkland and Maxwell (1961) describe the bottom 168 m as having penetrated rocks of "Cretaceous (?) age." The well record on file with the New Mexico Oil Conservation Division is unclear in this regard. As pointed out by Kelley (1977), a projection of the base of exposed Santa Fe formations in the Rio Puerco Valley only 10 km to the west of the well intersects the well at depths of about 450 to 600 m. Consequently, considerable unexposed faulting or increase in eastern dip must exist in the subcrop to the west of the Carpenter #1 Atrisco Well. Kelley (1977) has hypothesized that most of the vertical displacement (over 1600 m) is along the Sand Hill Fault about 7.5 km west of the Carpenter #1 Atrisco Well.

Water-table depths in the area of Figure 6-1 vary from 65 m at West Mesa #4 (our measurement) to 285 m at the former radar site well (Bjorkland and Maxwell 1961), which is about 3 km west-northwest of the Carpenter #1 Atrisco Well (see Figure 6-1). Probably the most significant aspect of the absolute elevation of the groundwater table beneath the area is a pronounced north-south trough 10 to 15 km wide approximately centered over the Llano de Atrisco. The trough described by Bjorkland and Maxwell (1961) is about 10 m

lower than the Rio Grande, 10 km to the east, and perhaps 35 m below the water level at the radar site well. These values are based on very few data from water wells; however, if these data are correct, the considerable hydraulic gradient on the west side of Figure 6-1 would imply significant eastward water movement.

Resistivity investigations in the Albuquerque area consisted first in 1979 of Schlumberger and combined Schlumberger-equatorial soundings at three locations, S1, S2, and S3 (see Figure 6-1). The soundings were followed in the same year by bipole-dipole mapping from two orthogonal bipole transmitter pairs BD1 and BD2, shown in Figure 6-1. Two dipole-dipole lines DD1 and DD2 (see Figure 6-1) were measured in 1980; the results are discussed in this chapter.

Surface magnetic profiles totaling 171 km were occupied as a portion of the current work. These profiles followed initial measurements of less than 10 km length made in 1980.

Shallow (< 30 m) temperature gradient measurements were made on the Llano de Atrisco during 1979 and 1980. Some anomalously high values ($> 100^{\circ}\text{C}/\text{km}$) in the shallow drillholes identified the need for deep gradient values, particularly below the water table. These measurements are currently being made in two holes that are 272 and 558 m deep. Preliminary data from these water monitor wells, drilled in the summer of 1981 by the U.S. Geological Survey and the City of Albuquerque with our cooperation, are presented in this discussion.

Discussion

Temperature Gradient Survey

Following the discovery of high shallow temperature gradients ($> 80^{\circ}/\text{km}$

in the upper 25 m) on the Llano de Atrisco in 1979 by eight drillholes, 52 additional holes were drilled during 1979 and 1980 in the area. The holes were positioned on a grid of 1 km spaced lines and stations, e.g., Lines 0, 1N, 2N, ..., 1S, 2S, ...; Stations 0, 1W, 2W, 3W, ... (see Figures 6-1 and 6-2). Most wells were drilled to 25 m to penetrate below the effect of the annual temperature wave, which is typically less than 15 m. Initial results of the 52 holes were presented by Parker and Jiracek (1980). Figure 6-2 contains contours of these shallow thermal gradient values after reoccupation of most sites and least-squares fitting of the temperature curves (Jiracek et al., 1981). The most significant observation is the high gradient anomaly, reaching $140^{\circ}\text{C}/\text{km}$, centered over Line 0, Station 5W (see Figure 6-2). A lesser anomaly of over $100^{\circ}\text{C}/\text{km}$ occurs about 2 km north. Both anomalies have small areas indicating shallow sources of limited extent.

Dipole-Dipole Resistivity

Bipole-dipole mapping on the Llano de Atrisco during the summer of 1979 exposed an unusual resistivity ridge of about 25 ohm-m on the west side of the Llano (see Figure 6-3). The uncovering of the near-coincidence of the resistivity ridge in Figure 6-3 and the maximum subsurface temperature gradient on the Llano de Atrisco (see Figure 6-2) warranted a detailed dipole-dipole survey. This survey was directed at detecting lateral resistivity variations which might explain the association of the resistivity high and the shallow hydrothermal anomaly.

Two dipole-dipole lines were traversed across the Llano de Atrisco during the summer of 1980. One line (DD1 in Figure 6-1) was run across the temperature gradient peak seen on survey Line 0 (see Figure 6-2). The traverse was 8 km long, used dipoles of 250 m, and dipole expansions were

Figure 6-2. Shallow temperature gradient map of Llano de Atrisco. Contours are given in °C/km.

Figure 6-3. Bipole-dipole total field apparent resistivity map of Llano de Atrisco obtained from VNS BD2 transmitter.

increased from $n = 1$ to 7. Another shorter line, DD2 which was 5 km long, was positioned 1.75 km north (see Figure 6-1) to cross a magnetic anomaly discovered during the initial field tests (Parker and Jiracek 1980).

Figure 6-4 contains the observed DD1 dipole-dipole results in pseudosection form and the calculated model results using the finite difference routine developed by Dey (1976). Although the observed and calculated results show a reasonably high degree of agreement, caution must be taken regarding the nonuniqueness of the corresponding resistivity model. In the model, the 80 and 20 ohm-m layers above 500 m represent the surficial layers and upper water-saturated zones seen in Schlumberger soundings S2 and S3 (see Figure 6-1; Parker and Jiracek 1980). The 8 ohm-m zone (see Figure 6-4) corresponds to the more conductive, saline waters probed by the soundings. The most significant feature of the DD1 results is a highly resistive zone detected and modeled between surface locations 5W and 7W (see Figure 6-4). The modeling suggests a resistive (60 ohm-m) projection into the shallow sequence and a possible draping of the 8 ohm-m zone over it. Modeling of the DD2 results in Figure 6-5 produced a similar feature which is displaced approximately 1 km to the west.

Magnetic Survey

A total field magnetic map of the Llano de Atrisco is presented in Figure 6-6. An areal coverage of 175 km^2 was obtained using Geometrics G-806 and G-816 proton precession magnetometers. Magnetic measurements were made 100 m apart on the survey lines indicated in Figure 6-1. Shorter east-west survey lines and some north-south lines were positioned closer than 1 km when deemed necessary for detail. Magnetic profiles for Lines 8S through 13N, after correction for diurnal magnetic variations and loop ties, are presented in

Figure 6-4. Dipole-dipole observed and calculated pseudosections and calculated resistivity model along Line 0 of Llano de Atrisco.

Figure 6-5. Dipole-dipole observed and calculated pseudosections and calculated resistivity model along Line 1.75 of Llano de Atrisco.

Figure 6-6. Total magnetic field map of Llano de Atrisco. Contours are given in nanoteslas.

Appendix A. Line 2S was not occupied because of restricted accessibility due to Interstate 40 and boundary fence lines. Readings over the surface lava flows of the Albuquerque volcanoes were too erratic to produce meaningful results.

The two temperature gradient highs (see Figure 6-2) and nearby magnetic anomalies (see Figure 6-6) disclosed by initial 1979 ground surveys were thought to have a causative relationship (Parker and Jiracek 1980). Although this relationship may exist, the very extensive magnetic survey of the Llano during 1980 (see Figure 6-6 and Appendix A) clearly shows that the resistive anomaly in Figures 6-3, 6-4, and 6-5 is nonmagnetic. Furthermore, the dipole-dipole results of DD2 (see Figure 6-5), which cross the largest magnetic anomaly in the entire survey area between Stations 3W and 4W on Line 1.75N, do not measure a corresponding large resistivity high. The highest dipole-dipole resistivity at depth is measured between Stations 5W and 6W on DD1 (see Figure 6-5), where the magnetic field is relatively flat (see Figure 6-6 and Appendix A, Line 0).

Three-dimensional modeling of the magnetic patterns in Figure 6-6 suggests sill-like bodies at shallow depths. The modeling was accomplished using a computer program written by Jiracek following the formulation of Bhattacharyya (1964). The program calculates the total field magnetic anomaly over a prism-shaped body with vertical sides and a flat top and bottom (see Figure 6-7). Any angle of magnetic polarization vector can be chosen relative to the geomagnetic field direction, thus allowing for both remanent and induced magnetism.

The relative contributions and directions of remanent and induced magnetism are unknown in the causative bodies producing the anomalies in

Figure 6-6. An igneous body that cooled through the Curie temperature in the last 700,000 years would be expected to have normal remanent polarization, which has been assumed in this model. More precisely, the total polarization direction has been assumed to be in the direction of the current geomagnetic field in the area, i.e., inclination (I) of 63° and declination (D) of 12.5°E (see Figure 6-7).

The choice of the susceptibility contrast (K) of the anomalous magnetic bodies and the surrounding sedimentary sequence has been made after several considerations. Using the method of Vacquier et al. (1951), the values $K = 2000 \times 10^{-6}$ and $K = 10,000 \times 10^{-6}$ (cgs units) are estimated for the anomalies intersected by survey lines 4N and 1.75N, respectively (see Figure 6-6). Using drillhole cuttings of volcanics from the two U.S. Geological Survey water monitor wells, volume corrected susceptibility values of 340×10^{-6} and 666×10^{-6} (cgs units), respectively, were measured. The latter measurement is from a well drilled north of the Albuquerque volcanoes (see Figure 6-1), which intersected the lava flows at a depth of 10 m. The former value is from a basaltic layer at a depth of 369 m drilled near a temperature gradient hole at Line 0, Station 5W (see Figure 6-2). Laboratory measurements do not reflect any remanent component to the polarization so the difference between the laboratory measurements and the calculation using the field anomalies may approximate the degree of remanence. Consequently, the ratio of remanent to induced magnetization may be a minimum of five and perhaps in excess of 20. Basalt samples from near Santa Fe, New Mexico, were measured to have ratios between 3.3 and 14.2 (Spiegel and Baldwin 1963). The highest effective susceptibility measured in these samples was reported to be 9600×10^{-6} (cgs units). This value has been assumed in our modeling as an effective susceptibility (i.e., one that includes combined remanent and induced components in polarization).

Figure 6-7. Magnetic prism model.

An example of the magnetic modeling appears in Figure 6-8 where the isolated anomaly centered on Line 4N (see Figures 6-1 and 6-6) has been closely matched. The prism body modeled in this case is 1.4 km in north-south extent and 1.0 km in east-west, with a depth of 275 m and a thickness of 87.5 m. This model is certainly not unique; however, the results are consistent with a body that is thin with its top very near the water-table depth. The sharper anomaly on Line 1.75N (see Figures 6-1 and 6-6) is likely shallower, possibly nearer to 200 m in depth.

There are at least 10 volcanic layers listed in the 2027-m well record from the nearby Carpenter #1 Atrisco Well; the thickest layer, however, is only 27 m. Resistivity logs of this wildcat oil test recorded resistivities in excess of 1000 ohm-m in some volcanic layers, and surface resistivity measurements on flows of the Albuquerque volcanoes by Brandwein (1974) yielded values of 2850 ohm-m. Such highly resistive layers would be easily detected by surface resistivity measurements unless they are thin (<50 m) or contain appreciable interconnected water. All of the above considerations lead to the conclusion that the resistive ridge detected by bipole-dipole mapping and dipole-dipole sounding-profiling is not due to subsurface volcanics.

Conclusions

An explanation of the resistive ridge and its relation to the thermal anomaly can be gleaned from a consideration of the gravity patterns (Birch 1980) over the test area (see Figure 6-9). It is quite obvious from the contours on the west side of the map that a residual gravity anomaly is present. Removal of a reasonable regional gradient yields an approximately 6 mgal north-northwest trending residual, centered roughly over Station 5W, Line

LLANO DE ATRISCO
LINE 4N MAGNETIC ANOMALY
CALCULATED

Figure 6-8. Calculated magnetic anomaly crossed on Line 4N of Llano de Atrisco. The hatched area is a plan view of the prism body.

0. Birch (1980) has computer modeled an east-west gravity profile passing directly through the Carpenter #1 Atrisco Well. This work modeled 2.4 g/cm^3 (Mesozoic) strata to be upfaulted to within 300 m of the surface only 2.5 km west of the Carpenter #1 Atrisco Well, which is not nearly as far west as suggested by Kelley (1977). The closed residual gravity anomaly evident in Figure 6-9 to the northwest of the oil well would suggest an additional ridge or knob on the upthrown block indicated by Birch (1980). Thus, the resistivity ridge in conjunction with the residual gravity anomaly is consistent with a shallow horst-like structure on the west side of the Llano de Atrisco. Additional detailed gravity measurements would better outline the structure. In addition, the driller's log of the water well at the radar site (Bjorkland and Maxwell 1961) terminates with the last entry from 418 to 422 m described as "rock, hard; cut bit."

Comparisons of geophysical measurements over the maximum thermal gradient high on the Llano de Atrisco are shown in Figure 6-10 for the thermal gradient, dipole-dipole pseudosection, and gravity profiles along Line 0. The magnetic profile along Line 1N, 1 km away, is also included. Here, it is again evident that the high resistivity anomaly between Stations 5W and 7W is related to the gravity anomaly and is not reflecting the magnetic body. This situation leads to the conclusion that the causative magnetic bodies, which are probably lava flows, are permeable to water flow and do not act as flow barriers. Furthermore, the gravity and resistivity highs are sensing an upthrown block of Cretaceous basement, which is relatively impermeable compared to the overlying Santa Fe beds. Minimum depth to the contact may be 200 to 250 m based on dipole-dipole modeling (see Figure 6-4 and 6-5).

The possibility that a buried ridge rises to about 250 m of the surface on the west side of the Llano de Atrisco suggests an explanation for the

Figure 6-10. Profiles of shallow thermal gradient, magnetic, gravity, and resistivity surveys on Llano de Atrisco. The thermal gradient anomaly is after Parker and Jiracek (1980).

hydrothermal anomaly there, namely, the forced groundwater convection model (see Figure 6-11) described by Morgan and Daggett (1981) and Morgan et al. (1981). In this model, heated groundwater from depth is brought closer to the surface by flow over subsurface constrictions or barriers. The large east-west hydraulic gradient discussed earlier in this area could be the driving mechanism for this heat transfer hypothesis. Since this area of the Llano de Atrisco has mapped faults (see Figure 6-1) which are presumably deep-seated (Kelley 1977), the possibility that all or a portion of the temperature anomaly is due to deep thermal convection cannot be ruled out. An alternate explanation of forced convection (see Figure 6-11) would lead to a lower maximum temperature at depth since the temperature is limited by the maximum depth of water circulation (Morgan et al. 1981).

Preliminary temperature measurements of the U.S. Geological Survey water monitoring well near Line 0, Station 5W (see Figures 6-1 and 6-2) have yielded a bottom-hole temperature of 34°C at a 372 m depth. The temperature gradient below the water table (265 m) was reported (Wilkins, personal communication 1981) to be a linear 30°C/km. Although these temperature measurements exceed those at similar depths elsewhere in the Albuquerque area (Jiracek et al. 1981), these values are not particularly encouraging with regard to future utilization of geothermal resources. The U.S. Geological Survey water monitoring well was positioned in the vicinity of our Line 0, Station 5W because of the possible geothermal significance. Positioning of the hole to the west of Station 5W (at about Line 0, Station 5.5W) appeared to be a better geothermal choice based on resistivity modeling (see Figure 6-4). However, the site chosen was more readily accessible than the preferred location.

It is interesting to note that the well record of the nearby Carpenter #1 Atrisco Well (see Figures 6-1 and 6-2) lists zones of "large volumes of water"

Figure 6-11. Hypothetical Rio Grande Rift forced groundwater convection system and expected surface heat flow profile. Relative temperatures in arbitrary units indicated in circles [after Morgan and Daggett (1981)].

at depths of 671, 889, and 1003 m. Extrapolation of the temperature gradient from the U.S. Geological Survey well leads to expected temperatures of 43, 50, and 53°C at these depths, respectively.

Acknowledgements

The field measurements described in this report were accomplished with the able assistance of many students. These were J. Coney, E. Dunn, S. Ganoe, M. Gerety, M. Herman, T. Holcombe, B. Honea, M. Parker, M. Mahoney, S. Raeuchle, T. Summers, Jr., M. Vaughn, R. Wasserman, and C. Zimmerman from the University of New Mexico and E. Gustafson from San Diego State University. The cooperation of the City of Albuquerque Water Resources and Parks Departments, A. Candelaria of Westland Development Company, and F. Bond of Volcano Ranch permitted our operations in the Albuquerque area. Two Geometrics G-816 magnetometers were loaned to us by Sandia Laboratories. Many beneficial discussions were had with F. S. Birch, A. Ramo of Sunoco Energy Development Company, C. A. Swanberg of New Mexico State University, P. Morgan of the Lunar and Planetary Institute, W. Turner of American Groundwater Consultants, G. Hammock of Gordon Herkenhoff and Associates, and D. Wilkins and his staff at the U.S. Geological Survey Water Resources Division in Albuquerque.

References

- Bachman, G. O., Marvin, R. F., Mehnert, H. H., and Merritt, V., 1975, K-Ar ages of the basalt flows at Los Lunas and Albuquerque, central New Mexico: Isochron/West, Report 13, p. 3-4.
- Bhattacharyya, B. K., 1964, Magnetic anomalies due to prism-shaped bodies with arbitrary polarization: *Geophysics*, v. 24, no. 4, p. 517-531.
- Birch, F. S., 1980, Geophysical evaluation of basin hydrologic characteristics in the central Rio Grande, Part I, gravity models of the Albuquerque-Belen Basin: U.S. Geological Survey, Contract No. 14-08-00001-17879, Final Report, 30 pp.
- Bjorklund, L. J., and Maxwell, B. W., 1961, Availability of groundwater in the Albuquerque area, Bernalillo and Sandoval Counties, New Mexico: New Mexico State Engineer's Office, Technical Report 21, 117 pp.
- Brandwein, S. S., 1974, Selected shallow electrical resistivity surveys at Volcano Cliffs, Bernalillo County, and Warm Springs, Sandoval County, New Mexico: University of New Mexico, Albuquerque, M.S. thesis, 139 pp.
- Dey, A., 1976, Resistivity modeling for arbitrarily shaped two-dimensional structures, Part II, user's guide to the FORTRAN algorithm RESIS2D: Lawrence Berkeley Laboratory, University of California, Berkeley, California, Report LBL-5283.
- Jiracek, G. R., Parker, M. D., Swanberg, C. A., and Morgan, P., 1981, Evaluation of the geothermal resource in the Albuquerque, New Mexico area: New Mexico Energy Research and Development Institute, Santa Fe, New Mexico, Final Report 2-67-2135, [In Preparation].
- Kelley, V. C., 1977, Geology of Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 33, 60 pp.
- Machette, M. N., 1978, Bernalillo County dump fault: New Mexico Bureau of Mines and Mineral Resources, Circular 163, p. 153-155.
- Morgan, P., and Daggett, P. H., 1981, Active and passive seismic studies of geothermal resources in New Mexico and investigations of earthquake hazards to geothermal development: New Mexico Energy Research and Development Institute, Santa Fe, New Mexico, Final Report 2-66-2203, 50 pp.
- Morgan, P., Harder, V., Swanberg, C. A., and Daggett, P. H., 1981, A groundwater convection model for Rio Grande rift geothermal resources: Geothermal Resources Council, Transactions, v. 5, p. 193-196.
- Parker, M. D., and Jiracek, G. R., 1980, Progress toward evaluating the geothermal resource in the Albuquerque, New Mexico area: Geothermal Resource Council, Transactions, v. 4, p. 229-232.

Spiegel, Z., and Baldwin, B., 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey, Water Supply Paper 1525, 258 pp.

Vacquier, V., Steenland, N. C., Henderson, R. G., and Zietz, I., 1951, Interpretation of aeromagnetic maps: Geological Society of America, Circular 47, 151 pp.

Wilkins, D., 1981, personal communication, U.S. Geological Survey, Water Resources Division, Albuquerque, New Mexico.

Appendix A

Profiles of Total Magnetic Field

Llano de Atrisco

Survey Lines 8S through 13N

Figure 6A-1. Llano de Atrisco magnetic survey Line 8S.

Figure 6A-2. Llano de Atrisco magnetic survey Line 7S.

Figure 6A-3, Llano de Atrisco magnetic survey Line 6S.

Figure 6A-4. Llano de Atrisco magnetic survey Line 5S.

Figure 6A-5. Llano de Atrisco magnetic survey Line 4S.

Figure 6A-6. Llano de Atrisco magnetic survey Line 3S.

Figure 6A-7. Llano de Atrisco magnetic survey Line 1S.

Figure 6A-8. Llano de Atrisco magnetic survey Line 0.

Figure 6A-9. Llano de Atrisco magnetic survey Line 1N.

Figure 6A-10. Llano de Atrisco magnetic survey Line 2N.

Figure 6A-11. Llano de Atrisco magnetic survey Line 3N.

Figure 6A-12. Llano de Atrisco magnetic survey Line 4N.

Figure 6A-13. Llano de Atrisco magnetic survey Line 5N.

Figure 6A-14. Llano de Atrisco magnetic survey Line 6N.

Figure 6A-15. Llano de Atrisco magnetic survey Line 7N.

Figure 6A-16. Llano de Atrisco magnetic survey Line 8N.

Figure 6A-17. Llano de Atrisco magnetic survey Line 9N.

Figure 6A-18. Llano de Atrisco magnetic survey Line 10N.

Figure 6A-19. Llano de Atrisco magnetic survey Line 11N.

Figure 6A-20. Llano de Atrisco magnetic survey Line 12N.

Figure 6A-21. Llano de Atrisco magnetic survey Line 13N.

Chapter 7

Resource Assessment in Southwest New Mexico

(Catron, Dona Ana, Grant, Hidalgo, Luna, and Sierra Counties)

Part 1

Electrical Resistivity Studies*

Introduction

The southern part of the Rio Grande Rift passes through Dona Ana and Luna counties. The rift is tectonically active, thermally anomalous, and distinguished throughout its length by the combination of high heat flow, recently active volcanoes, exceptionally deep basins and late Quaternary faulting (Seager and Morgan 1979). Thus, the area has the potential for geothermal resources.

Direct-current electrical resistivity soundings, using the Schlumberger array, are often employed for groundwater and geothermal reconnaissance. The technique can determine the thickness and resistivity of subsurface layers, thereby determining the depths to the water table and bedrock. The resistivity of the aquifer is related to the quality of the water. Geothermal areas can be detected indirectly since hot water has lower electrical resistivity than cold water and hot rock has lower resistivity than cold rock. Unfortunately, salty water and clays also have low resistivity, so the method is not foolproof. Possible resources identified by this technique must be confirmed by measuring subsurface temperatures and drilling test wells.

*The principal author of Chapter 7, Part 1 is Dr. Charles T. Young, Assistant Professor, Department of Geology and Geological Engineering, Michigan Technological University.

The sources of data used for this analysis are given in the figure captions and text as the data are discussed. These data sets and other electrical studies are included in an index map and bibliography prepared by Jiracek (1980b). Many of the cited studies were too shallow to be useful for geothermal studies. Notable exceptions are the deep penetration magnetotelluric studies by Geotronics Corporation (1979). These measurements penetrate tens of miles into the earth and are capable of detecting gross structures which are probably responsible for the high heat flow observed in New Mexico. Geotronics Corporation has conducted magnetotelluric measurements along a line from El Paso to the Animas Valley and in a grid on the Jornada del Muerto near Truth or Consequences. These data are proprietary.

Discussion

Hidalgo County

The most extensive geoelectrical study for geothermal resources in Hidalgo County is that of Smith (1977, 1978) covering the Lightning Dock area approximately 10 miles southwest of Lordsburg. The data are reported in the New Mexico Geological Society Guidebook (Callendar, Wilt, and Clemons 1978) and are not repeated here.

Catron County

Many Schlumberger soundings have been made in the San Augustin Plains area in Catron County (Zhody et al. 1976). These data are currently being analyzed and will be available in a USGS open-file report (Zhody, personal communication 1980).

Luna and Dona Ana Counties

Figure 7-1 summarizes the survey areas and shows faults mapped or inferred by Seager and Morgan (1979) and Seager (personal communication 1980). New data reported here are contained in the areas indicated by boxes in Luna County marked Nutt and Dwyer. Columbus data are from Swanberg et al. (1981). The irregular box in Dona Ana County gives the location of data from Young (1978, 1979, 1981), Jackson (1976), and Zhody et al. (1976). Additional data are available on the Las Alturas geothermal field from Smith (1977, 1978), but they are too detailed for the purposes of this discussion.

Columbus. The region east of Columbus, New Mexico, has been surveyed for geothermal resources by Swanberg et al. (1981) using electrical resistivity, airborne electromagnetic, gravity, and temperature measurements from test holes. A summary of the airborne electromagnetic data is shown in Figure 7-2. The low apparent resistivities from these data coincide very well with ground resistivity data. The regions of highest immediate geothermal potential are the low-resistivity zones near Columbus. The existence of warm water under the eastern low-resistivity zones has not been demonstrated.

Dwyer. Two new areas in Luna County were explored during the current work, which are marked by Dwyer and Nutt on the key map of Figure 7-1. These areas were surveyed by electric profiling and sounding to see whether the concealed faults could be located and whether these faults had associated low resistivities, which would indicate high geothermal potential.

The Dwyer profile (see Figure 7-3) lies approximately 10 miles southeast of Faywood Hot Springs and may enclose an intersection of two concealed faults. This profile displayed in Figure 7-4 shows an abrupt change in deep resistivity from tens of ohm-m in the south, to generally 6 to 13 ohm-m in the north. This change is interpreted as a fault. The soundings over the lowest

Figure 7-1. Survey areas in Luna and Dona Ana counties. Survey areas enclosed by heavy black lines are discussed in the text. Background map shows main landmarks and faults in the survey areas from Seager (personal communication, 1980). The dashed lines are faults which are concealed or covered. The solid lines are surface faults. The hatchures are on the downthrown side of the faults.

Figure 7-2. Apparent resistivities near Columbus, New Mexico, calculated from airborne electromagnetic measurements (Barringer Input System) from Swanberg et al. (1981). The hatched areas are the lowest resistivities, 3 ohm-m or less. The heavy lines mark ground dc-resistivity profiles. The apparent resistivities were measured along these profiles with a Schlumberger array of electrode spacing $AB/2 = 800$ m.

Figure 7-3. Survey line C-C' on the Dwyer 15-Minute Quadrangle in northern Luna County. The tick marks indicate the center of the Schlumberger array. The double-ended arrows labeled 7251 and 7252 mark Schlumberger vertical electric soundings. A fault is interpreted from an abrupt change in deep apparent resistivity and is represented by conventional geologic symbols.

Figure 7-4. Profile C-C' from the Dwyer 15-Minute Quadrangle. The data are plotted as a pseudo-depth section showing the apparent depth of the resistivity values at $AB/2 = 100$ m and 800 m. The flat-layered models which best match the sounding data are shown as stratigraphic columns labeled 7251 and 7252. The triangles mark the center of the sounding electrode array. Apparent resistivities and depths are given in ohm-m and meters, respectively.

resistivity areas show a layer of 10-ohm-m material approximately 380-m (1140-ft) thick adjacent to the fault, with higher resistivities to the north. The interpreted fault is plotted in Figure 7-2. The location and throw of this fault are known from the resistivity data. The strike and curvature, if any, are not known. Imprecise data has led to discrepancies between the profile data and the sounding interpretations. The geological conclusions, however, are not affected.

Nutt. The profile and soundings near Nutt (see Figure 7-5) were conducted to search for faults and associated low-resistivity zones. Abrupt changes in deep resistivities of profile data were again interpreted as faults (see Figures 7-5, 7-6, and 7-7). The layered-earth models of the sounding data indicate that there is a low-resistivity layer in the area between 200 and 500 m (600 to 1500 ft). This layer is probably thickest and has lowest resistivity southwest of the Nutt crossroads. The interpreted concealed faults and the throws are plotted in Figure 7-5. The strike is unknown and is plotted to correspond to logical geologic structure.

Dona Ana County

This analysis includes data sets from Young (1978, 1979, 1981), Zhody et al. (1976), and Jackson (1976). Additional data for the Las Alturas geothermal field are available in Smith (1977) and Jiracek and Smith (1976). These data are too detailed to fit onto the present map.

All but two of the profiles presented here are reinterpretations of some of the 215 vertical electric soundings of Zhody et al. (1976) and Jackson (1976). The data need to be reinterpreted because:

Figure 7-5. Survey lines A-A' and B-B' on the Nutt 15-Minute Quadrangle. The faults are interpreted from abrupt changes in deep apparent resistivity and are represented by the conventional geologic symbols.

Figure 7-6. Profile A-A' from the Nutt 15-Minute Quadrangle. The data are plotted as a pseudo-depth section showing the apparent depth of the resistivity values at $AB/2 = 100$ m and 800 m. The flat-layered models which best match the sounding data are shown as stratigraphic columns labeled 7211, 7212, and 7241. The triangles mark the center of the sounding-electrode array. Apparent resistivities and depths are given in ohm-m and meters, respectively.

Figure 7-7. Profile B-B' from the Nutt 15-Minute Quadrangle. The data are plotted as a pseudo-depth section showing the apparent depth of the resistivity values at $AB/2 = 100$ m and 800 m. The flat-layered models which best match the sounding data are shown as stratigraphic columns labeled 7223 and 7221. The triangles mark the center of the sounding-electrode array. Apparent resistivities and depths are given in ohm-m and meters, respectively.

- (1) the original open-file reports are collections of sounding curves and computer-generated models that need to be presented on maps and in profile form to be understood; and
- (2) the computer-generated models use one layer for each sounding datum, which is geologically misleading because a small bump on the sounding curve is automatically interpreted as a thin layer of extremely high or low resistivity. Such a bump can be caused equally well by lateral inhomogeneity.

These data have been reinterpreted by modeling with the least number of layers required to model the gross features of the sounding curves. The match between the data and the model is still quite good and the resulting geological models are considerably easier to interpret. These data are combined with extensive hydrogeological and geological data by Wilson et al. (1981).

Figure 7-8 shows the locations of measurement stations and the contours of lowest apparent resistivity. The minimum resistivity values were generally found at electrode spacings of $AB/2 = 200$ meters or greater. Thus, the values represent the main aquifer under the stations. Experience in Dona Ana County suggests the following ranking of the data:

- (1) 20 to 50 ohm-m: high-quality groundwater, very unlikely to contain geothermal components. These resistivities occur just north of Las Cruces and south of Hatch in agricultural areas and south of Hatch in the foothills of the Sierra de Las Uvas Mountains.
- (2) 10 to 20 ohm-m: medium-quality groundwater, may contain geothermal components. These resistivities are quite common in the survey areas. For example, a vertical electric

Figure 7-8. Contours of the lowest-apparent resistivity at each station. Background map is a 1975 Dona Ana County highway map (scale, 1:126,720 or one inch equals three miles). The dots mark the station locations. Data are from Jackson (1976), Zhody et al. (1976), and Young (1978, 1979, 1981).

sounding by Smith (1977) in the Las Alturas geothermal field resulted in a minimum resistivity of about 16 ohm-m at an electrode spacing of $AB/2 = 400$ m.

- (3) below 10 ohm-m: low-quality groundwater. The low resistivity is caused either by high total-dissolved solids, by high temperature, or by both. These resistivities are found on the mesa west and south of Las Cruces, near San Diego Mountain north of Las Cruces, northwest of El Paso, and in the Mesilla Valley at scattered locations.

The vertical electric-sounding data in Dona Ana County generally show high-resistivity surface layers, a low- or medium-resistivity aquifer, and a medium- or high-resistivity bottom layer, called the electrical basement. In Dona Ana County, this basement may consist of compact sandstone, limestone, or dense volcanic rock. Figure 7-9 shows contours for the depth to electrical basement determined by the USGS multi-layer models. These contours accurately outline major basins in the Mesilla Valley. Kinks and crowded contours may represent subsurface faults.

The soundings have been organized as profiles by the USGS as shown on Figure 7-10. New Mexico State University profiles N-N' and M-M' have been added and the longest profiles have been reinterpreted.

Interpreted Profiles

The sounding data from each station along these profiles were modeled by first making a reasonable estimate for the minimum number of layers that could account for the observed data, neglecting minor bumps, and then finding a

Figure 7-10. Locations of profiles in Dona Ana County. All of the profiles from Zhody et al. (1976) and Jackson (1976) have been shown for completeness. Only the longest profiles are interpreted in this analysis. Profiles N-N' and M-M' use data from Young (1978).

suitable combination of layer thicknesses and resistivities that produced a calculated sounding-curve matching the field data. These calculations are performed with an interactive computer program similar to the programs described by Koefoed (1979). The interpreted profiles are presented in Figures 7-11 through 7-22.

The accuracy of the model is limited by the quality of the data, the patience and experience of the person doing the modeling, and the fact that more than one model may fit a sounding curve. An attempt was made to minimize the equivalence problem by using as few layers as possible and avoiding layers with extremely high or low resistivity values.

Almost all the sounding models have multiple near-surface layers too thin to label on the drawings. These layers, which have been omitted, are generally unimportant to geothermal and hydrological interpretations. The profiles are discussed from geographic north to south and only with respect to the geothermal-related features.

Profile 0 crosses Interstate 25 near Rincon (see Figure 7-11). The lowest resistivities are found under the Rio Grande, the town of Rincon, and the interstate highway. Other studies (Young 1981 and Lohse 1978) have identified this area as having high geothermal potential. The contours in Figure 7-8 show that this low-resistivity zone extends south approximately six miles to the north face of San Diego Mountain. The profile extends east to the Jornada del Muerto, where the low-resistivity layer dips down to at least 600 m (1800 ft) below the surface.

Profile A (see Figure 7-12) crosses the northern outskirts of Las Cruces and extends out into the Jornada del Muerto. A broad high-resistivity zone under stations A6, A7, A8, A9, and A10 is probably a buried extension of the Dona Ana Mountains about five miles to the north. The low resistivities along

Figure 7-11. Cross-sectional structural interpretation of Profile 0 across Interstate 25 near Rincon, New Mexico. The data are taken from Jackson (1976). Triangles mark the center of the vertical electrode sounding arrays. The heavy bars shown below the triangles are interfaces interpreted from the sounding data. Resistivities and depths of the layers are given in ohm-m and meters, respectively.

Figure 7-12. Cross-sectional structural interpretation of Profile A across the northern outskirts of Las Cruces and extending out into the Jornada del Muerto. Triangles mark the center of the vertical electrode sounding arrays. The heavy bars below the triangles are interfaces interpreted from the sounding data. Resistivities and depths of the layers are given in ohm-m and meters, respectively.

Figure 7-13. Cross-sectional structural interpretation of Profile B extending westward from the western outskirts of Las Cruces. Triangles mark the center of the vertical electrode sounding arrays. The heavy bars below the triangles are interfaces interpreted from the sounding data. Resistivities and depths of the layers are given in ohm-m and meters, respectively.

Figure 7-14. Cross-sectional structural interpretation of Profile C east of Las Cruces, north of the Las Alturas geothermal field. Triangles mark the center of the vertical electrode sounding arrays. The heavy bars below the triangles are interfaces interpreted from the sounding data. Resistivities and depths of the layers are given in ohm-m and meters, respectively.

Figure 7-15. Cross-sectional structural interpretation of Profile N lying along a north-south line east of Las Cruces. The data are taken from Young (1978). Triangles mark the center of the vertical electrode sounding arrays. The heavy bars below the triangles are interfaces interpreted from the sounding data. Resistivities and depths of the layers are given in ohm-m and meters, respectively.

Figure 7-16. Cross-sectional structural interpretation of Profile M approximately parallel to Profile N on the east side of Tortugas Mountain. The data are taken from Young (1978). Triangles mark the center of the vertical electrode sounding arrays. The heavy bars below the triangles are interfaces interpreted from the sounding data. Resistivities and depths of the layers are given in ohm-m and meters, respectively.

Figure 7-17. Cross-sectional structural interpretation of Profile D about three miles south of Profile B and extending from the outskirts of Las Cruces into the desert near La Mesa. The data are taken from Jackson (1976). Triangles mark the center of the vertical electrode sounding arrays. The heavy bars below the triangles are interfaces interpreted from the sounding data. Resistivities and depths of the layers are given in ohm-m and meters, respectively.

Figure 7-18. Cross-sectional structural interpretation of Profile E across the Rio Grande and Interstate Highway 10 about two miles north of the Black Mesa lava flow. The data are taken from Jackson (1976). Triangles mark the center of the vertical electrode sounding arrays. The heavy bars below the triangles are interfaces interpreted from the sounding data. Resistivities and depths of the layers are given in ohm-m and meters, respectively.

Figure 7-19. Cross-sectional structural interpretation of Profile I across the Mesilla Valley near San Miguel and Mesquite. The data are taken from Jackson (1976). Triangles mark the center of the vertical electrode sounding arrays. The heavy bars below the triangles are interfaces interpreted from the sounding data. Resistivities and depths of the layers are given in ohm-m and meters, respectively.

Figure 7-20. Cross-sectional structural interpretation of Profile R which extends from near Kilbourne Hole past Berino and into the low hills to the east. The data are taken from Jackson (1976). Triangles mark the center of the vertical electrode sounding arrays. The heavy bars below the triangles are interfaces interpreted from the sounding data. Resistivities and depths of the layers are given in ohm-m and meters, respectively.

Figure 7-21. Cross-sectional structural interpretation of Profile F west of Profile EE less than six miles from the international boundary between New Mexico and Mexico. The data are taken from Jackson (1976). Triangles mark the center of the vertical electrode sounding arrays. The heavy bars below the triangles are given in ohm-m and meters, respectively.

Figure 7-22. Cross-sectional structural interpretation of Profile EE east of Profile F less than six miles from the international boundary between New Mexico and Mexico. The data are taken from Zhody et al. (1976). Triangles mark the center of the vertical electrode sounding arrays. The heavy bars below the triangles are given in ohm-m and meters, respectively.

this line occur at depths of 300 m (900 ft) or more in the Jornada del Muerto. These resistivities represent moderate geothermal potential. The low-resistivity layer and the faults inferred along either side of the Dona Ana Mountains have high geothermal potential.

Profile B (see Figure 7-13) extends westward from the western outskirts of Las Cruces. The interpreted profile shows low resistivities 150 m (450 ft) below the surface to the west. The desert in the La Mesa area is a low-resistivity area of considerable geothermal interest to commercial exploration companies. Sounding B4 shows high resistivities within about 50 m (150 feet) of the surface. This layer is interpreted as a horst block which may be associated with Picacho Peak, which is an andesite volcano located three miles to the north.

Profile C (see Figure 7-14) is east of Las Cruces, north of the Las Alturas geothermal field. This line is an eastward extension of Profile B. This interpretation shows considerable faulting and shows low resistivities north of Las Alturas and east of Tortugas Mountain. A high-resistivity horst block is shown as a possible buried northern extension of Tortugas Mountain. This block may be a groundwater divide that confines the hot water to the Las Alturas area.

Profile N (see Figure 7-15) lies along a north-south line, east of Las Cruces. The profile passes through the Las Alturas geothermal field. Layer resistivities as low as four to five ohm-m are associated with this geothermal field. These low resistivities suggest that the field continues at least to Station N6 or E8 to the south.

Profile M (see Figure 7-16) is approximately parallel to Profile N and lies approximately two and one-half miles to the east, on the east side of Tortugas Mountain. The lowest resistivities on this line are about 15 ohm-m,

at locations approximately due east of Las Alturas. This region is probably a separate hydrologic regime from Las Alturas due to a buried high-resistivity ridge which forms an aquitard. The ridge is visible in detailed geoelectric cross-sections (Jiracek, personal communication 1980a). Thus, the area of Profile M has less geothermal potential than the area of Profile N. All of the resistivities of 15 ohm-m are potential geothermal resources. The most promising geothermal areas within the zones are probably along the faults. The faults on all the profiles are inferred from the abrupt changes to electrical basement. More detailed groundwork is necessary to locate these faults precisely.

Profile D (see Figure 7-17) is about three miles south of Profile B and also extends from the outskirts of Las Cruces into the desert around La Mesa. The geological interpretation of this profile is approximately the same as that for Profile B, which indicates better quality groundwater near Las Cruces and poorer quality, possibly geothermal, water to the west. The horst block separating the two regions was not detected by the soundings, but probably lies between Stations D6 and D7, as shown in Figure 7-17.

Profile E (see Figure 7-18) crosses the Rio Grande and Interstate Highway 10 about two miles north of the Black Mesa lava flow, or about four miles north of the town of San Miguel. The low resistivity at Station E8 suggests that the Las Alturas geothermal field may extend this far south. There is a 1200 ohm-m high-resistivity layer at a depth of approximately 80 m (240 ft) at Station E6, west of the interstate highway. This result is interpreted as a horst block which could be a part of north-south faulting in the Mesilla Valley. The low-resistivity layer shown beneath that high-resistivity layer could be an artifact in the data caused by the normal field procedure of moving the current electrodes laterally off the resistivity block, into more

conductive material. In certain cases, it may be impossible to tell the difference between lateral- and depth-variations in resistivity. The data have been interpreted as a lateral structural change. The region of greatest geothermal potential in Profile E is probably that bounded by the faults on either side of Station E8.

Profile I (see Figure 7-19) crosses the Mesilla Valley near the towns of San Miguel and Mesquite. There is an abrupt change in the depth-to-electrical basement under Station I5, west of the interstate highway. This horst may be an underground extension of Vado Hill, located four miles south, or the block in Profile E. The greatest geothermal potential is probably along the interstate highway, east of Station I5.

Profile R (see Figure 7-20) extends from near Kilbourne Hole to the west, past Berino and the State of New Mexico Port of Entry, and up into low hills to the east. The western stations show a conductive layer with an upper boundary at depths of 300 to 1200 m (900 to 3600 ft), similar to that of Profiles B and D. The eastern half of the profile shows numerous basement faults and low-resistivity zones, which have high geothermal potential (Young 1981).

The southernmost profiles F-F' (see Figure 7-21) and EE-EE' (see Figure 7-22) lie less than six miles from the international boundary between New Mexico and Mexico. The westernmost profile, F-F', shows deep, low resistivities below 400 m (1200 ft) as do the other profiles across the desert near La Mesa. The eastern Profile EE-EE', with 19 soundings, shows more detail, including possible basement faulting under Stations 59, 60, and 62. The lowest resistivities on the profile occur under Stations 51, 47, and 50. These low resistivities are probably caused by dissolved salts rather than by geothermal waters. The low resistivity zones are in an agricultural area that

has many irrigation wells into the aquifer; if the aquifer was characterized by elevated temperatures, it would be widely known.

Conclusions

The faults interpreted from the profiles in Dona Ana County are plotted on Figure 7-23. The interpreted fault locations are plotted between the resistivity stations. Determinations of more precise locations are not possible. The direction of throw of the faults is known, but the orientations are not known. These faults, when associated with low resistivities, coincide with the areas of greatest geothermal potential.

Acknowledgements

The author wishes to express his gratitude to those colleagues and assistants involved in this project, especially Sandra Adams, Justine Gilkey, David Lynch, Pete Ostlender, Bob Sanders, Luis Salazar, and John Viescas.

Figure 7-23. Faults interpreted from resistivity profiles near Las Cruces.

References

- Callendar, J. F., Wilt, J. C., and Clemons, R. E., eds., 1978, Land of Cochise, southern Arizona: New Mexico Geological Society, 29th Field Conference Guidebook, 372 pp.
- Geotronics Corporation, 1979, Nonexclusive magnetotelluric maps: Geotronics Corporation, Austin, Texas.
- Jackson, D. B., 1976, Schlumberger soundings in the Las Cruces, New Mexico area: U.S. Geological Survey, Open-File Report 76-231, 170 pp.
- Jackson, D. B. and Bisdort, R., 1975, Direct current soundings on the La Mesa surface near Kilbourne and Hunt's holes, in Seager, W. R., Clemons, R. E., and Callendar, J. F., eds., Guidebook of the Las Cruces country; New Mexico Geological Society, 26th Field Conference Guidebook, p. 273-275.
- Jiracek, G. R., 1980a, Personal communication, Department of Geological Sciences, San Diego State University, San Diego, California.
- Jiracek, G. R., 1980b, Available geoelectrical studies, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low-temperature geothermal resource assessment program, fiscal year 1979: National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia, p. 7/1 - 7/16.
- Jiracek, G. R. and Smith, C., 1976, Deep resistivity investigations at two Known Geothermal Resource Areas (KGRA's) in New Mexico, Radium Springs and Lightning Dock: New Mexico Geological Society, Special Publication 6, p. 71-76.
- Koefoed, O., 1979, Geosounding principles, I: Elsevier Scientific Publishing Company, New York, 276 pp.
- Lohse, R. L., 1980, Heat-flow study of Dona Ana County, southern Rio Grande Rift, New Mexico: New Mexico State University, Las Cruces, New Mexico, M.S. thesis, 101 pp.
- Seager, W. R., 1980, Personal communication, Department of Earth Sciences, New Mexico State University, Las Cruces, New Mexico.
- Seager, W. R. and Morgan, P., 1979, The Rio Grande Rift in southern New Mexico, west Texas and northern Chihuahua, in Riecker, R. E., ed., Rio Grande Rift, tectonics and magmatism: American Geophysical Union, Washington, D. C., p. 87-106.
- Smith, C., 1977, The electrical evaluation of three southern New Mexico geothermal areas: University of New Mexico, Albuquerque, New Mexico, M.S. thesis, 113 pp.

- Smith, C., 1978, Geophysics, geology and geothermal leasing status of the Lightning Dock KGRA, Animas Valley, New Mexico, in Callendar, J. F., Wilt, J. C., and Clemons, R. E., eds., Land of Cochise, southern Arizona: New Mexico Geological Society, 29th Field Conference Guidebook p. 343-348.
- Swanberg, C. A., Morgan, P. and Young, C. T., 1981, Electrical exploration and geothermal gradient studies near Columbus, New Mexico: New Mexico Energy Research and Development Institute, Report 2-68-2204, 60 pp.
- Wilson, C., White, R., Orr, B., and Roybal, G. R., 1981, Water resources of the Mesilla and Rincon valleys and adjacent areas, New Mexico: U.S. Geological Society, Open-File Report 81-487.
- Young, C., 1978, Resistivity measurements near Tortugas Mountain: Arts and Science Research Center, New Mexico State University, Las Cruces, New Mexico, unpublished report, 16 pp.
- Young, C., 1979, Electrical exploration for geothermal resources near San Diego Mountain, New Mexico: New Mexico Energy Research and Development Institute, Report 2-67-2232, 20 pp.
- Young, C., 1981, Geothermal exploration with electrical methods near Vado, Chamberino and Mesquite, New Mexico, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low-temperature geothermal resource assessment program, fiscal year 1980: National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia, p. 4/1 - 4/16.
- Zhody, A. A. R., 1980, Personal communication, U.S. Geological Survey, Denver, Colorado.
- Zhody, A. A. R., Bisdorf, R. J., and Gates, J. S., 1976, Schlumberger soundings in the lower Mesilla Valley of the Rio Grande, Texas and New Mexico: U.S. Geological Survey, Open-File Report 76-234, 77 pp.

Part 2

Temperature Studies in Southwestern New Mexico*

Introduction

A number of data sets were analyzed in order to assess the geothermal potential of southwestern New Mexico, including the counties of Catron, Dona Ana, Grant, Hidalgo, Luna, Sierra, and Socorro (see Figure 7-24). The data sets analyzed included actual temperatures; bottom-hole temperature gradients; temperatures predicted by SiO_2 , Na-K-Ca, and Na-K-Ca (Mg corrected) geothermometry; tectonics; complete Bouguer gravity anomalies; and residual Bouguer gravity anomalies. Additional information and insight was obtained from a statewide lineament study.

Existing Data Sets

Measured Temperatures

The actual temperature data of springs and wells (see Figure 7-25) come from multiple sources, namely: USGS WATSTORE and GEOTHERM files; Chaturvedi (1980); Lohse (1980, 1981); Lohse et al. (1981a, 1981b); Morgan et al. (1980); and Swanberg (1980a, 1980b, 1980c).

The recorded temperatures range from approximately 10° to 100°C . The locations of the anomalously warm temperatures ($\geq 40^\circ\text{C}$) are shown by the solid symbols in Figure 7-25. In order to increase the size of the data base, all temperatures recorded to depths less than 150 m (~ 500 ft) have been included on Figure 7-25. A cut-off depth of 150 m was chosen in order not to bias

*The principal author of Chapter 7, Part 2 is Richard L. Lohse, Geothermal Field Engineer, New Mexico Energy Institute, New Mexico State University.

Figure 7-24. Location map of the area in southwestern New Mexico surveyed for geothermal potential.

Figure 7-25. Actual temperatures ($^{\circ}\text{C}$) of springs and of wells less than 150 m deep in southwestern 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, Chaturvedi (1980), Lohse (1980, 1981), Lohse et al. (1981a, 1981b), Morgan et al. (1980), and Swanberg (1980a, 1980b, 1980c).

Figure 7-25 by showing the locations of the deeper wells instead of areas of anomalous temperatures. Assuming a surface temperature of 20°C and a normal temperature gradient of 40°C/km, the temperature at 150 m would be 26°C, which is not considered to be an anomalous temperature. Consequently, the solid symbols in Figure 7-25 show the locations of anomalous temperatures within the upper 150 m section of the earth's crust and not merely the sites of deeper wells. Temperatures in the range of 20° to 40°C are not shown as solid symbols in Figure 7-25 because some of the wells in this group could be normal while others are actually anomalous. For this reason, wells with measured temperatures of 30° to 40°C are shown separately in Figure 7-26. The locations of anomalous temperatures at depths less than 150 m are, therefore, shown by the solid symbols of Figure 7-25 and all the symbols in Figure 7-26.

Wells with recorded bottom-hole temperatures are shown in Figure 7-27 and are classified by computed bottom-hole temperature gradients, assuming a surface temperature of 20°C. Table 7-1 summarizes the computed bottom-hole temperature-gradient data. The anomalous bottom-hole temperature gradients depicted by the solid symbols in Figure 7-27 indicate areas of elevated temperatures within the earth's crust. Since Figures 7-25 and 7-26 do not contain actual temperatures recorded at depths greater than 150 m and Figure 7-27 does not contain spring data, all three data sets must be used together in order to determine all of the areas characterized by anomalously warm temperatures.

Geothermometry Data

Figures 7-28, 7-29, and 7-30 show SiO_2 , Na-K-Ca, and Na-K-Ca (Mg corrected) geothermometry data, respectively. Unlike Figures 7-25, 7-26, and 7-27, solid symbols in Figures 7-28, 7-29, and 7-30 do not necessarily

Figure 7-26. Locations of springs and of wells less than 150 m deep in southwestern New Mexico with actual temperatures between 30° and 40°C. Surface temperatures are reported for springs. Some of the wells are of unknown depth. The data are compiled from USGS WATSTORE and GEOTHERM files, Chaturvedi (1980), Lohse (1980, 1981), Lohse et al. (1981a, 1981b), Morgan et al. (1980), and Swanberg (1980a, 1980b, 1980c).

Figure 7-27. Bottom-hole temperature gradients ($^{\circ}\text{C}/\text{km}$) of wells in southwestern New Mexico for an assumed surface temperature of 20°C . The data are compiled from USGS WATSTORE and GEOTHERM files, Chaturvedi (1980), Lohse (1980, 1981), Lohse et al. (1981a, 1981b), Morgan et al. (1980), and Swanberg (1980a, 1980b, 1980c).

Table 7-1.

Computed bottom-hole temperature gradients for wells in southwestern New Mexico. The data are compiled from USGS WATSTORE and GEOTHERM files, Chaturvedi (1980), Lohse (1980, 1981), Lohse et al. (1981a, 1981b), Morgan et al. (1980), and Swanberg (1980a, 1980b, 1980c).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Catron</u>	33°59.9'	108°01.7'	13.5	30	-217
	33°59.4'	108°01.7'	13.7	76	-83
	33°58.2'	108°02.5'	12.8	73	-99
	33°58.1'	108°34.3'	18.5	36	-42
	33°58.1'	108°16.5'	13.2	21	-324
	33°58.1'	108°16.2'	15.5	37	-122
	33°57.5'	108°04.6'	11	63	-143
	33°57.2'	108°00.8'	11.2	70	-126
	33°56.5'	108°19.9'	13	24	-292
	33°55.9'	108°14.3'	14.5	18	-306
	33°55.7'	108°07.6'	14	49	-122
	33°55.7'	108°13.8'	14	21	-286
	33°55.7'	108°11.2'	13.2	38	-179
	33°55.6'	108°13.8'	13.9	30	-203
	33°55.5'	108°13.8'	13.4	27	-244
	33°55.2'	108°25.7'	17.7	108	-21
	33°55.0'	108°22.9'	15.2	99	-48
	33°54.8'	108°09.8'	14.1	40	-148
	33°54.8'	108°08.4'	13.3	49	-137
	33°54.2'	108°13.6'	11	55	-164
	33°53.9'	108°06.5'	13.7	36	-175
	33°53.8'	108°02.5'	16	61	-66
	33°52.6'	108°15.5'	14.2	30	-193
	33°52.0'	108°02.1'	13.3	46	-146
	33°50.5'	108°18.7'	16.9	105	-30
	33°50.1'	108°18.6'	15.6	59	-75
	33°49.5'	108°13.5'	14.5	335	-16
	33°48.5'	108°14.2'	15.5	18	-250
	33°48.4'	108°05.3'	13	38	-184
	33°48.0'	108°08.8'	13.5	34	-191
	33°47.8'	108°19.8'	14.5	38	-145
	33°47.8'	108°18.9'	13	18	-389
	33°46.9'	108°24.6'	9.5	24	-438
	33°46.9'	108°12.3'	15.5	30	-150
	33°46.8'	108°21.0'	15.2	58	-83
	33°46.0'	108°17.2'	12.5	18	-417
	33°45.1'	108°19.3'	11	27	-333
	33°45.0'	107°49.0'	32	350	34
	33°43.8'	108°03.4'	26	229	26

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Catron</u>	33°37.3'	108°11.0'	28	411	19
	33°34.1'	108°13.8'	19.5	329	-2
	33°28.7'	108°27.1'	22	191	10
	33°13.5'	108°14.5'	32	183	66
	33°13.5'	108°13.2'	32	183	66
<u>Dona Ana</u>	32°49'	106°38'	31	306	36
	32°48.0'	106°52.0'	35	300	50
	32°45.7'	106°52.3'	21	183	5
	32°45.0'	107°15.7'	17.5	21	-119
	32°42.4'	106°57.7'	25	116	43
	32°42.2'	106°58.1'	25	116	43
	32°42'	107°02'	23	79	38
	32°42'	106°49'	25	118	43
	32°41.9'	106°59.1'	25	116	43
	32°40.6'	107°12.9'	19	22	-45
	32°40.4'	107°12.0'	20	38	0
	32°40.2'	107°11.9'	18	38	-53
	32°38.9'	106°27.7'	26.5	219	30
	32°38.0'	107°00.0'	34	180	78
	32°37.9'	107°01.6'	27	89	79
	32°37.9'	106°59.6'	36	175	91
	32°37.6'	106°59.9'	36.0	175	91
	32°37.3'	107°14.4'	22	97	21
	32°37.2'	107°00.9'	17	18	-167
	32°37.2'	106°25.8'	26.5	228	29
	32°37'	107°15'	22	101	20
	32°36.8'	107°14.8'	22	100	20
	32°36.5'	106°58.9'	51.8	150	212
	32°36.4'	106°58.8'	53	150	220
	32°36.3'	106°59.1'	52.7	150	218
	32°36.2'	107°17.5'	19.2	25	-32.4
	32°36.1'	107°00.9'	17.6	15	-158
	32°35.7'	107°09.8'	19.3	15	-46
	32°32.9'	107°14.1'	19.8	50	-3.4
	32°31.6'	106°42.6'	26	213	28
	32°31.6'	106°40.7'	25	286	17
	32°31.4'	106°43.0'	27	241	29
	32°29.8'	106°53.2'	23.5	280	13
	32°29.6'	106°54.1'	21	32	31
	32°29.2'	106°49.5'	19	17	-59
	32°29'	106°55'	21	32	31
	32°29'	106°54'	23.5	284	12
	32°28.9'	106°26.7'	26.5	132	49

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Dona Ana</u>	32°28.7'	106°24.8'	24.5	72	63
	32°28.5'	106°26.7'	29	232	39
	32°28.4'	106°30.8'	21	24	42
	32°28.0'	106°30.2'	25.5	76	72
	32°28'	106°40'	25	161	31
	32°27.8'	106°39.4'	25	161	31
	32°27.7'	106°27.1'	29	310	29
	32°27.0'	106°36.0'	52	910	35
	32°26.7'	106°26.7'	26	159	38
	32°26.7'	106°26.6'	29	240	37
	32°26.6'	106°26.7'	24.5	159	28
	32°26.5'	106°58.7'	20	15	0
	32°25.8'	106°40.9'	29	366	25
	32°25.6'	106°51.8'	19	124	-8
	32°25.6'	106°30.7'	23	58	52
	32°25.4'	107°05.3'	30.8	250	43
	32°25.2'	106°29.7'	25	166	30
	32°25.0'	106°29.2'	26.5	182	36
	32°24.6'	106°29.8'	27	323	22
	32°24.5'	106°28.2'	28	305	26
	32°24.4'	107°14.8'	23.7	115	32
	32°24.3'	106°28.3'	26.6	264	25
	32°24.3'	106°28.2'	28	295	27
	32°24.2'	106°28.3'	27.5	305	25
	32°24.1'	106°51.2'	18	49	-41
	32°24.0'	106°32.6'	21.5	39	38
	32°24.0'	106°26.7'	26.5	101	64
	32°24'	106°45'	25	213	23
	32°23.8'	106°29.5'	24.5	247	18
	32°23.7'	106°42.5'	25	183	27
	32°23.7'	106°30.7'	22	157	13
	32°23.6'	106°48.4'	21.5	99	15
	32°23.5'	106°29.6'	23	163	18
	32°23.4'	106°29.5'	25.5	270	20
	32°23.3'	106°44.3'	26	305	20
	32°23.2'	106°30.8'	20.5	40	13
	32°23.2'	106°48.6'	20.5	215	2
	32°23.2'	106°29.6'	24.5	152	30
	32°23.2'	106°29.1'	26.5	251	26
	32°23.2'	106°29.0'	24	132	30
	32°23.2'	106°28.8'	26	244	25
	32°23.2'	106°28.3'	25	212	24
	32°23.2'	106°27.7'	27	107	65

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Dona Ana</u>	32°23.0'	106°29.0'	24.5	154	29
	32°23.0'	106°44.5'	25.5	305	18
	32°23.0'	106°29.5'	19.5	152	-3
	32°23'	106°49'	21.5	99	15
	32°23'	106°49'	20.5	215	2
	32°23'	106°45'	26	305	20
	32°23'	106°41'	28	358	22
	32°22.9'	106°41.5'	33	340	38
	32°22.9'	106°31.1'	22.5	39	64
	32°22.9'	106°28.4'	28.5	224	38
	32°22.8'	106°41.5'	33.4	340	39
	32°22.8'	106°40.5'	28	358	22
	32°22.7'	107°17.7'	23.9	80	49
	32°22.6'	106°47.7'	17	30	-100
	32°22.6'	106°28.5'	25.5	222	25
	32°22.5'	106°50.1'	17	74	-41
	32°22.3'	106°48.7'	18	119	-17
	32°22.2'	106°51.0'	18.5	40	-38
	32°22.0'	106°40.0'	34	350	40
	32°21.9'	106°27.0'	25	238	21
	32°21.8'	106°50.8'	19	49	-20
	32°21.7'	106°50.6'	18.5	30	-50
	32°21.2'	106°43.1'	67.9	265	181
	32°21.2'	106°25.8'	24	137	29
	32°21.1'	106°45.4'	22.5	198	13
	32°21.0'	106°50.9'	18	23	-87
	32°20.7'	106°50.1'	16	91	-44
	32°20.7'	106°46.2'	23.5	200	18
	32°20.5'	106°45.9'	23	206	15
	32°20.2'	106°47.5'	18	73	-27
	32°20.2'	106°50.8'	16	91	-44
	32°20.2'	106°46.8'	26.5	189	34
	32°20.1'	106°50.4'	16	36	-111
	32°20.1'	106°48.5'	19	152	-7
	32°20.1'	106°47.6'	19	152	-7
	32°20.0'	106°46.8'	20	61	0
	32°19.9'	106°48.3'	18	73	-27
	32°19.8'	106°50.8'	16	36	-111
	32°19.8'	106°50.5'	20	218	0
	32°19.8'	106°47.7'	18.5	20	-75
	32°19.8'	106°46.6'	20	110	0
	32°19.7'	106°46.3'	19	110	-9
	32°19.7'	106°45.0'	21.3	130	10
	32°19.6'	106°48.6'	18	97	-21
	32°19.6'	106°48.5'	21	218	5
	32°19.5'	106°46.8'	19.5	116	-4

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Dona Ana</u>	32°19.4'	106°45.6'	19	116	-9
	32°19.3'	106°45.1'	23.3	208	16
	32°19.2'	106°46.4'	19.5	116	-4
	32°19.1'	106°44.6'	24	223	18
	32°18.8'	106°45.5'	21.5	90	18
	32°18.8'	106°45.3'	24	222	18
	32°18.8'	106°44.6'	25	213	23
	32°18.8'	106°44.3'	24	152	26
	32°18.8'	106°43.6'	54	235	145
	32°18.7'	106°44.8'	24.5	207	22
	32°18.5'	106°47.6'	21	607	2
	32°18.5'	106°47.6'	18	193	-10
	32°18.5'	106°46.7'	22	390	5
	32°18.5'	106°45.2'	25.5	213	26
	32°18.4'	106°51.5'	16	172	-23
	32°18.4'	106°46.4'	19.5	24	-21
	32°18.3'	106°50.8'	19	129	-8
	32°18.3'	106°47.1'	21.5	52	29
	32°18.3'	106°44.8'	26	185	32
	32°18.0'	106°43.5'	25	128	39
	32°18'	106°48'	21	610	2
	32°18'	106°47'	21.5	52	29
	32°18'	106°47'	22	24	83
	32°18'	106°45'	24	152	26
	32°17.9'	106°48.1'	17.8	100	-22
	32°17.9'	106°45.2'	21	91	11
	32°17.9'	106°44.3'	24	120	33
	32°17.9'	106°44.2'	25.5	160	34
	32°17.8'	106°52.1'	16	172	-23
	32°17.8'	106°51.7'	19	129	-8
	32°17.8'	106°45.3'	21.5	86	17
	32°17.4'	106°49.7'	16.5	61	-57
	32°17.4'	106°39.0'	23.0	65	46
	32°17.3'	106°43.9'	28.1	150	54
	32°17.2'	106°48.5'	17	37	-81
	32°17.2'	106°43.0'	62	300	140
	32°17.2'	106°42.8'	33.4	30	446
	32°17.1'	106°44.6'	20	118	0
	32°17.0'	106°43.1'	63.4	300	141
	32°17.0'	106°43.6'	50	360	83
	32°17.0'	106°43.5'	48	145	193
	32°17.0'	106°43.2'	34.1	30	469
	32°16.9'	106°46.5'	15.5	110	-41
	32°16.9'	106°43.5'	50.85	360	82

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Dona Ana</u>	32°16.9'	106°25.2'	30	320	31
	32°16.8'	106°43.6'	30.3	30	342
	32°16.8'	106°43.2'	20.5	118	4
	32°16.7'	106°44.1'	22.4	30	79
	32°16.7'	106°46.2'	17.5	245	-10
	32°16.6'	106°45.0'	20.3	90	4
	32°16.5'	106°46.5'	17	107	-28
	32°16.5'	106°46.0'	18	85	-24
	32°16.4'	106°46.0'	19	143	-7
	32°16.3'	106°46.8'	17	107	-28
	32°16.3'	106°44.9'	20	186	0
	32°16.2'	106°48.2'	18	66	-31
	32°16.2'	106°45.3'	18.3	25	-69.6
	32°16.2'	106°43.0'	32.1	30	404
	32°16.2'	106°43.3'	43	108	213
	32°16.1'	107°01.0'	36	320	50
	32°16.1'	106°49.7'	18	64	-31
	32°16.1'	106°49.0'	18	33	-60
	32°16.1'	106°43.2'	41.4	80	268
	32°16.0'	107°00.5'	36	320	50
	32°16.0'	106°42.5'	13	152	-46
	32°16'	106°43'	27	148	47
	32°15.9'	106°44.3'	13	152	-46
	32°15.9'	106°43.4'	36	148	108
	32°15.9'	106°43.3'	36.5	148	111
	32°15.9'	106°43.1'	42.2	100	222
	32°15.9'	106°42.9'	32.3	30	410
	32°15.8'	107°00.8'	36	320	50
	32°15.8'	106°58.8'	32	366	33
	32°15.8'	106°45.2'	18	97	-21
	32°15.8'	106°44.6'	18	98	-21
	32°15.8'	106°43.8'	41	80	262
	32°15.8'	106°43.6'	24.5	80	56
	32°15.7'	106°49.3'	19.5	40	-12
	32°15.7'	106°48.2'	18	65	-31
	32°15.7'	106°42.5'	27	148	47
	32°15.5'	106°43.8'	22	72	28
	32°15.5'	106°58.2'	21.5	153	10
	32°15.5'	106°43.8'	42	100	220
	32°15.3'	106°44.6'	18	96	-21
	32°15.2'	106°27.7'	24	165	24
	32°14.7'	106°43.1'	20.5	73	7
	32°14.5'	106°43.6'	20.5	73	7
	32°14.4'	107°12.3'	22.9	70	42

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Dona Ana</u>	32°14.4'	106°42.6'	43	108	213
	32°14.2'	106°46.5'	18.5	140	-11
	32°14.2'	106°46.5'	23	94	32
	32°14.0'	106°44.9'	17	244	-12
	32°14.0'	106°44.9'	21	45	22
	32°14.0'	106°44.5'	20	40	0
	32°14.0'	106°24.8'	23.5	187	19
	32°14'	106°44'	20.5	73	7
	32°13.9'	106°45.5'	17	244	-12
	32°13.8'	106°45.8'	18	27	-73
	32°13.7'	106°42.0'	24	156	26
	32°13.6'	106°47.3'	18	113	-18
	32°13.6'	106°42.5'	18.5	215	-7
	32°13.5'	106°52.9'	21.6	110	14
	32°13.5'	106°45.8'	18	61	-33
	32°13.4'	106°44.9'	18.5	366	-4
	32°13.4'	106°42.5'	20	148	0
	32°13.3'	106°44.3'	21	94	11
	32°13.2'	106°45.6'	18.5	141	-11
	32°13.1'	106°45.4'	20	188	0
	32°13.1'	106°45.3'	20	95	0
	32°13.1'	106°45.2'	19	209	-5
	32°13.1'	106°45.2'	22	186	11
	32°12.9'	106°44.3'	18.5	91	-16
	32°12.7'	106°44.8'	19	146	-7
	32°11.0'	106°42.3'	19	113	-9
	32°10.8'	106°41.9'	23.3	251	13
	32°10.7'	106°42.0'	24.5	42	107
	32°10.7'	106°40.2'	29	122	74
	32°10.5'	106°41.4'	20	92	0
	32°10.5'	106°40.4'	29	122	74
	32°10.5'	106°39.8'	29	122	74
	32°10.1'	106°44.5'	23	207	14
	32°10.0'	106°44.6'	21.5	80	19
	32°10.0'	106°42.7'	26	524	11
	32°10.0'	106°41.3'	19	79	-13
	32°10'	106°45'	21.5	213	7
	32°10'	106°40'	25	122	41
	32°09.9'	106°44.8'	21.5	213	7
	32°09.9'	106°39.6'	25	122	41
	32°09.8'	106°44.2'	19.5	27	-18
	32°09.3'	106°40.9'	18	20	-101
	32°09.2'	106°39.3'	30	76	132
	32°09.1'	106°39.3'	31.5	76	151

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Dona Ana</u>	32°09.0'	106°38.8'	31.5	76	151
	32°09.0'	107°03.0'	33	240	54
	32°08.8'	106°39.3'	32	76	158
	32°08.6'	106°51.8'	31	209	53
	32°08.4'	106°52.1'	31	209	53
	32°08.4'	106°39.9'	31	209	53
	32°08.4'	106°38.8'	27.5	79	95
	32°08.2'	106°51.8'	26.2	260	24
	32°08.0'	106°51.0'	35	490	31
	32°07.5'	106°39.5'	24	152	26
	32°07.0'	106°39.0'	23	160	19
	32°06.7'	106°42.4'	19.5	215	-2
	32°06.7'	106°40.9'	18	37	-55
	32°05.8'	106°41.0'	19.5	76	-7
	32°05.8'	106°38.1'	29	398	23
	32°04.5'	106°36.0'	36	219	73
	32°04.5'	106°26.2'	26	259	23
	32°04.4'	106°40.5'	18.5	62	-24
	32°04.4'	106°40.3'	22	186	11
	32°04.3'	106°38.5'	19	40	-25
	32°04.2'	106°38.4'	15	18	-283
	32°04.1'	106°38.4'	31	153	72
	32°04.1'	106°37.5'	20.5	23	22
	32°04.1'	106°36.8'	31	153	72
	32°04.0'	106°40.1'	15	37	-137
	32°04.0'	106°38.1'	20	100	0
	32°04.0'	106°36.9'	31	153	72
	32°04'	106°37'	31	153	72
	32°04'	106°40'	22	186	11
	32°04'	106°36'	27	171	41
	32°03.8'	106°39.7'	22.5	45	55
	32°03.7'	106°39.7'	23	518	6
	32°03.5'	106°40.9'	21	46	22
	32°03.4'	106°41.2'	20.5	47	11
	32°03.2'	106°52.3'	34	131	107
	32°03.0'	106°59.5'	34	131	107
	32°02.7'	106°37.5'	23	366	8
	32°02.3'	106°36.0'	23.5	82	43
	32°01.8'	106°40.9'	21.5	40	37
	32°01.5'	106°53.5'	33	172	76
	32°01.0'	106°37.0'	32	244	49
	32°00.9'	106°53.7'	31	115	96
	32°00.8'	106°54.3'	31.2	115	97
	32°00.6'	106°35.6'	24.5	82	55
	32°00.5'	106°37.8'	19	43	-23
	32°00.3'	106°36.1'	26	137	44

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Dona Ana</u>	32°00'	106°36'	24.5	64	70
	32°00'	106°36'	24	123	33
	32°59.4'	107°01.8'	27.0	110	64
	31°58.2'	106°49.8'	28.6	115	74
	31°58.0'	106°58.0'	38	55	327
	31°57.8'	106°52.2'	27.2	110	65
	31°57.7'	106°56.9'	26.8	90	75
	31°57.0'	107°01.5'	20.3	30	10
	31°56.9'	106°59.9'	45	206	121
	31°56.5'	107°00.3'	28	183	44
	31°56.4'	106°49.0'	27	138	51
	31°56.3'	106°39.3'	33.3	213	62
	31°56'	107°00'	28	183	44
	31°55.4'	106°55.5'	20.3	25	10
	31°54.8'	107°00.8'	22.5	60	42
	31°54.5'	107°00.3'	26.1	130	47
	31°54'	106°51'	27	138	51
	31°53.8'	107°00.1'	24.3	95	45
	31°53.3'	107°00.1'	25.6	130	43
	31°53'	106°40'	25.9	65	108
	31°52'	106°40'	26.5	90	98
	31°52'	106°41'	28.0	160	51
	31°52'	106°42'	28.9	140	64
	31°52'	106°42'	29.7	175	55
	31°52'	106°39'	26.1	80	76
	31°51.8'	106°41.4'	28.8	180	50
	31°51.4'	106°38.4'	26.6	70	94
	31°51.2'	106°41.6'	29.2	180	52
	31°51'	106°43'	28.5	170	53
	31°51'	106°41'	28.5	160	56
	31°50.7'	106°41.4'	28.8	170	53
	31°50.7'	106°40.7'	29.3	175	53
	31°50'	106°42'	29.1	170	55
	31°50'	106°37'	27.3	85	86
	31°50'	106°40'	27.7	135	65
	31°50'	106°40'	29.3	170	55
	31°49.5'	106°38.8'	31	306	36
	31°49.5'	106°37.6'	31	306	36
<u>Grant</u>	33°08.1'	108°46.7'	24.5	122	37
	33°08.0'	108°53.7'	23	24	125
	33°06.8'	108°35.4'	15	41	-122
	33°06.6'	108°57.8'	15.7	24	-179
	33°04.8'	108°56.3'	15.5	23	-196

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Grant</u>	33°02.5'	108°42.1'	18.5	610	-2
	33°01.6'	108°42.8'	19.5	31	-16
	33°01.3'	108°47.3'	20.5	162	3
	33°00.7'	108°40.0'	16.5	24	-146
	32°59.0'	108°36.0'	33	91	143
	32°58.7'	108°35.5'	35	91	165
	32°57.9'	108°36.8'	20	125	0
	32°56.2'	108°57.5'	16.5	100	-35
	32°56.1'	108°54.1'	19	103	-10
	32°55.8'	107°59.9'	14	56	-107
	32°55.7'	108°36.3'	19.5	134	-4
	32°54.5'	108°35.7'	33.5	91	148
	32°54.1'	108°54.1'	19	103	-10
	32°53.7'	108°43.0'	18.5	198	-8
	32°53.2'	108°33.6'	19.5	116	-4
	32°51.2'	108°37.2'	19.5	30	-17
	32°50.3'	108°41.7'	18.5	38	-39
	32°50.2'	108°30.4'	18.5	23	-65
	32°49.0'	107°56.2'	14.5	94	-59
	32°48.9'	108°28.5'	16	24	-167
	32°48.8'	108°03.3'	25.5	644	9
	32°48.8'	107°55.5'	14.5	32	-172
	32°48.5'	107°55.2'	21.6	18	89
	32°48.2'	108°03.3'	25.5	65	85
	32°46.8'	108°05.9'	32	610	20
	32°45.2'	108°22.3'	20	183	0
	32°45.1'	107°53.8'	19	46	-22
	32°45.1'	108°22.6'	20	201	0
	32°44.9'	108°09.1'	16.6	107	-32
	32°44.8'	107°52.2'	18	46	-43
	32°44.2'	108°10.2'	20	144	0
	32°44.2'	108°10.0'	19.5	118	-4
	32°44.1'	108°09.9'	19.5	82	-6
	32°43.5'	107°54.2'	17	30	-100
	32°43.0'	108°17.9'	22.5	213	12
	32°42.8'	108°20.1'	21.1	234	5
	32°42.7'	108°36.8'	16.5	23	-152
	32°42.7'	108°19.8'	20.5	183	3
	32°42.6'	108°25.4'	17	30	-100
	32°42.6'	108°19.8'	21	273	4
	32°42.4'	108°19.9'	21.8	274	7
	32°42.2'	108°36.8'	18	20	-100
	32°40.6'	107°53.1'	19	20	-50
	32°40.6'	108°19.8'	21	274	4

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Grant</u>	32°40.2'	108°02.1'	62	158	266
	32°39.8'	107°53.2'	18	26	-77
	32°38.6'	108°07.7'	31	269	41
	32°38.3'	107°52.3'	19	23	-43
	32°37.7'	107°52.5'	23	224	13
	32°36.8'	108°45.8'	26.5	104	63
	32°36.4'	108°05.2'	24.5	197	23
	32°34.5'	108°13.8'	18.7	50	-26
	32°34.3'	108°27.4'	16.5	46	-76
	32°34.0'	108°01.4'	41	33	636
	32°33.9'	108°37.5'	18.5	82	-18
	32°33.5'	108°07.5'	19.5	122	-4
	32°27.8'	108°26.6'	16	23	-174
	32°16.8'	108°29.7'	21	91	11
	32°16.1'	108°26.0'	28	143	56
	32°16.1'	108°20.2'	20.5	50	10
	32°13.2'	108°31.1'	20	51	0
	31°11.1'	108°18.0'	21.5	77	19
	32°10.8'	108°23.2'	24.5	102	44
	32°10.7'	108°23.2'	23.5	183	19
	32°09.5'	108°31.5'	19.5	50	-10
	32°07.6'	108°17.2'	18	49	-41
	32°06.6'	108°29.3'	19	43	-23
	32°05.8'	108°24.2'	19.5	50	-10
	32°05.5'	108°19.2'	23.5	77	45
	31°57.2'	108°28.2'	19.5	15	-33
	31°56.0'	108°20.2'	23	107	28
	31°55.5'	108°20.3'	24	212	19
	31°55.3'	108°20.3'	23.8	212	18
	31°52.3'	108°24.4'	19.5	88	-6
<u>Hidalgo</u>	32°42.9'	108°53.7'	22	24	83
	32°35.0'	108°47.5'	20	24	0
	32°25.0'	108°59.0'	35	136	110
	32°14.8'	108°50.7'	19	41	-24
	32°14.5'	108°54.7'	19	28	-36
	32°14.3'	108°50.7'	19.5	28	-18
	32°14.1'	108°33.7'	19.5	76	-7
	32°12.9'	108°32.7'	23.5	244	14
	32°10.5'	108°51.0'	121	2256	45
	32°10.0'	109°02.0'	36	310	52
	32°08.8'	108°49.9'	95.5	33	2288
	32°08.8'	108°49.9'	98	29	2690

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Hidalgo</u>	32°08.7'	108°52.8'	19	85	-12
	32°08.7'	108°50.5'	33.5	86	157
	32°08.7'	108°50.3'	52	37	865
	32°08.1'	108°51.2'	19	87	-11
	32°08.1'	108°50.9'	20.5	65	8
	32°07.8'	108°52.8'	21	62	16
	32°07.5'	108°51.2'	15.5	46	-98
	32°06.8'	108°53.6'	19	33	-30
	32°05.7'	108°50.7'	22	63	32
	32°05.7'	108°50.7'	24	154	26
	32°03.7'	108°53.5'	16.5	43	-81
	32°03.2'	108°54.3'	19	39	-26
	32°03.2'	108°51.9'	23	37	81
	32°01.8'	108°59.9'	23	69	43
	32°00.4'	109°01.3'	22.7	23	117
	32°00.3'	109°01.9'	23	23	130
	31°58.2'	108°50.0'	20	78	0
	31°58.0'	108°50.0'	20	79	0
	31°57.2'	108°48.3'	20	93	0
	31°56.3'	108°49.3'	21	65	15
	31°56.3'	109°02.3'	21	51	20
	31°55.5'	109°00.5'	21.1	23	48
	31°51.4'	108°47.9'	25.5	83	66
	31°47.8'	108°37.1'	23.5	67	52
	31°42.8'	108°19.3'	32	743	16
	31°42.2'	108°33.9'	26	79	76
	31°42.0'	108°20.5'	18	49	-41
	31°40.3'	108°17.3'	20	48	0
	31°39.8'	108°28.8'	20	52	0
	31°38.7'	108°19.9'	22	183	11
	31°38.1'	108°15.7'	25	126	40
	31°37.3'	108°15.8'	23.5	62	56
	31°35.8'	108°20.2'	20	54	0
	31°34.9'	108°17.2'	21	228	4
	31°34.6'	108°28.8'	25	282	18
	31°34.2'	108°13.5'	21.5	35	43
	31°31.6'	108°20.4'	18.5	62	-24
	31°27.2'	108°29.9'	22	274	8
	31°22.3'	108°13.5'	18.5	142	-11

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
Luna	32°35.7'	107°45.6'	24.5	137	33
	32°35.3'	107°51.9'	19	122	-8
	32°35.2'	107°48.1'	21	76	13
	32°32.2'	107°49.9'	20	15	0
	32°30.1'	108°03.9'	17	34	-88
	32°29.5'	107°27.0'	25.5	133	41
	32°29.4'	107°22.0'	25.5	133	41
	32°22.0'	107°40.0'	47	320	84
	32°16.3'	107°46.3'	21.5	122	12
	32°15.5'	107°47.0'	32	244	49
	32°15.1'	107°35.0'	39	338	56
	32°15.1'	107°43.3'	19	72	-14
	32°15.1'	107°42.8'	18	72	-28
	32°15.0'	107°34.0'	39	338	56
	32°14.8'	107°33.0'	34.5	130	112
	32°14.8'	107°22.9'	22	42	48
	32°14.5'	107°34.2'	21	38	26
	32°14.5'	107°34.2'	24	87	46
	32°14.3'	107°56.8'	21	61	16
	32°14.3'	107°33.5'	24.5	114	39
	32°14.2'	107°49.9'	20	84	0
	32°14.2'	107°55.5'	26	597	10
	32°13.9'	107°56.0'	26	457	13
	32°13.7'	107°49.3'	20.5	122	4
	32°13.5'	107°57.3'	21	107	9
	32°13.5'	107°57.3'	22	120	17
	32°10.2'	107°29.2'	21.5	70	21
	32°10.2'	107°26.8'	24.5	152	30
	32°10.2'	107°26.0'	24	70	57
	32°10.1'	107°29.1'	20.5	70	7
	32°09.7'	107°28.1'	22	70	29
	32°09.3'	107°28.9'	31.5	305	38
	32°09.1'	107°44.9'	20.5	67	7
	32°08.8'	107°30.9'	20	70	0
	32°08.6'	107°28.9'	28.5	305	28
	32°08.2'	107°42.9'	20.4	49	8
	32°04.8'	107°43.6'	18.6	23	-61
	32°02.7'	107°55.0'	20	28	0
	31°59.0'	107°42.7'	14.5	19	-289
	31°58.4'	107°41.3'	21	126	8
	31°58.2'	107°26.3'	23.5	91	38
	31°57.7'	107°39.2'	24	131	31

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Luna</u>	31°53.2'	107°33.6'	30.5	305	34
	31°52.7'	107°53.5'	19	352	-3
	31°51.5'	107°35.1'	29	192	47
	31°51.0'	107°36.5'	33	161	81
	31°47.2'	107°40.7'	29	99	91
<u>Sierra</u>	33°27.4'	107°41.1'	17.5	134	-19
	33°27.3'	107°43.7'	14.5	38	-145
	33°26.1'	107°26.8'	20	17	0
	33°25.0'	106°54.0'	34	410	34
	33°22.5'	106°44.7'	20	38	0
	33°19.6'	106°24.5'	24.5	109	41
	33°14.3'	106°30.3'	23.3	109	30
	33°13.3'	106°32.3'	26.1	287	21
	33°13.3'	107°15.3'	45.5	32	797
	33°08.2'	107°15.3'	44.5	30	817
	33°07.9'	107°14.8'	21	37	27
	33°07.8'	107°15.4'	40	32	625
	33°07.7'	107°15.5'	40	65	308
	33°07.6'	107°15.2'	42	60	367
	33°07.3'	107°17.3'	26.4	123	52
	33°07.2'	107°17.8'	25.5	115	48
	33°07.2'	107°17.3'	25.5	125	44
	33°07.2'	107°16.0'	40	75	267
	33°07.2'	107°15.3'	39	63	302
	33°07.1'	107°17.1'	24.2	92	46
	33°06.9'	107°17.6'	19.2	18	-44
	33°06.3'	107°17.4'	25	118	42
	33°04.0'	107°18.0'	33	458	28
	33°02.3'	107°18.3'	20	47	0
	32°59.5'	107°23.9'	18.5	22	-68
	32°59.0'	107°19.2'	24	114	35
	32°58.8'	107°20.0'	23	104	29
	32°58.7'	107°22.2'	21.3	38	34
	32°58.6'	107°22.2'	21	33	30
	32°58.5'	107°21.5'	22	92	22
	32°58.4'	107°20.3'	22	92	22
	32°58.4'	107°02.8'	22	80	25
	32°58.3'	107°20.8'	23	104	29
	32°58.3'	107°20.8'	19.2	43	-19
	32°58.3'	107°20.0'	24	114	35

Table 7-1. (continued).

County	Latitude	Longitude	Temperature (°C)	Depth (m)	Computed Bottom-Hole Temperature Gradient* (°C/km)
<u>Sierra</u>	32°58.2'	107°20.2'	19	49	-20
	32°58.2'	107°20.2'	19	73	-14
	32°58.2'	107°20.1'	21	85	12
	32°58.1'	107°20.2'	22	79	25
	32°58.0'	107°29.7'	21.5	79	19
	32°57.3'	107°29.9'	21.2	59	20
	32°56.0'	107°33.5'	18.5	76	-20
	32°54.2'	107°20.4'	24	66	61
	32°53.9'	107°19.7'	20	69	0
	32°53.3'	107°19.9'	23	61	49
	32°53.1'	107°18.1'	20.5	39	13
	32°52.6'	107°18.8'	20.5	39	13
	32°51.8'	107°18.5'	20	18	0
	32°50.2'	107°19.3'	19.5	30	-17
	32°49.7'	107°19.2'	20	37	0
	32°48.3'	107°13.1'	19.5	21	-24
	32°48.0'	106°54.0'	36	300	53
<u>Socorro</u>	33°34.0'	107°36.0'	36	250	64

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

Figure 7-28. SiO_2 geotemperatures ($^{\circ}\text{C}$) of springs and wells in southwestern New Mexico. The data are compiled from Swanberg (1980a, 1980c) and from the data files of Southland Royalty Company made available by Jodry (1981).

Figure 7-29. Na-K-Ca geotemperatures ($^{\circ}\text{C}$) of springs and wells in southwestern New Mexico. The data are compiled from Swanberg (1980a, 1980c) and from the data files of Southland Royalty Company made available by Jodry (1981).

Figure 7-30. Na-K-Ca (Mg corrected) geotemperatures (°C) of springs and wells in southwestern New Mexico. The data are compiled from Swanberg (1980d) and from the data files of Southland Royalty Company made available by Jodry (1981).

indicate anomalous data. Areas thought to be thermally anomalous would be those areas where both the SiO_2 (see Figure 7-28) and Na-K-Ca (see Figure 7-29) geothermometers are in agreement and indicate elevated base temperatures. When the Mg correction is applied to the Na-K-Ca geothermometry data, there is a decrease in the estimated base temperatures (see Figure 7-30). However, measured temperatures ($>90^\circ\text{C}$) have already exceeded those estimated by Na-K-Ca (Mg corrected) geothermometry in the Animas Valley Lightning Dock KGRA area, which lies approximately 15 kilometers (~ 10 miles) north-northwest of Animas, New Mexico (see Figure 7-24).

Tectonic Features

Figure 7-31 is a tectonic map illustrating two different periods of faulting during the Pliocene to Pleistocene epochs (~ 1 to 4 m.y.) and during the late Quaternary Period (<1 m.y.). Also shown on the map are Quaternary and late Pliocene volcanic rocks, major volcanic centers, and the locations and ages of dated basaltic rocks. Northwest trending normal faults predominated during the Pliocene to Pleistocene epochs. The late Quaternary Period has been dominated by north-south trending normal faults that have persisted into the Holocene Epoch as evidenced by the less than 3000 to 4000 year fault-scarp, which cuts a Holocene fan on the eastern side of the Organ Mountains (Seager 1981), approximately 20 kilometers (~ 12 miles) to the east of Las Cruces, New Mexico (see Figure 7-24).

The majority of the Quaternary and late Pliocene volcanic rocks and their volcanic centers appear to be located in regions characterized by north-south trending normal faults. Most of the age dates associated with these volcanic rocks are approximately of the same age as the faults. The close agreement of age and location between faults and volcanic rocks suggests that the faulting and volcanism are contemporaneous.

Figure 7-31 · Late Cenozoic faults, volcanic rocks and vents, and locations and ages of dated basaltic rocks. The data are taken from Callender and Seager (1980), Seager et al. (1981), and Aldrich and Laughlin (1981).

Gravity Data

Figures 7-32 and 7-33 are complete and residual Bouguer gravity anomaly maps for the study area, respectively. The complete and residual gravity maps have a range of gravity values from -245 to -115 mgals and -20 to +55 mgals, respectively. The residual Bouguer gravity anomaly data were generated by Aiken et al. (1978) using the complete Bouguer gravity data of Cordell et al. (1978) as a base map and correcting for regional elevation variations. The residual Bouguer gravity map (see Figure 7-33) clearly shows strong northwest-southeast structural trends probably extending into the basement (Paleozoic and Precambrian strata ?), which passes through Grant, Luna, Dona Ana counties (see Figure 7-24). Also shown in Figure 7-33 are north-south trending structural zones through Socorro, Sierra, and Dona Ana counties and the eastern one-third of Luna County. Dona Ana County is generally situated at the intersection of the two zones of structural weakness.

Discussion

An analysis of the geological and geophysical data suggests several trends which are summarized in a series of graphical presentations. Figure 7-34 displays the sites of the anomalous data based on actual temperatures (see Figure 7-25), actual temperatures between 30° and 40°C (see Figure 7-26), and bottom-hole temperature gradients (see Figure 7-27). Anomalous data are defined as actual temperatures greater than or equal to 30°C or bottom-hole temperature gradients 60°C/km or above. Figure 7-35 is a composite of the sites of anomalous data based on SiO_2 , Na-K-Ca, and Na-K-Ca (Mg corrected) geothermometers (see Figures 7-28, 7-29, and 7-30, respectively). Anomalous

Figure 7-32. Complete Bouguer gravity anomaly map of southwestern New Mexico [from Cordell et al. (1978)].

Figure 7-33. Residual Bouguer gravity anomaly map of southwestern New Mexico [from Aiken et al. (1978)].

Figure 7-34. Sites in southwestern New Mexico characterized by anomalous actual well and spring temperatures ($\geq 30^{\circ}\text{C}$), bottom-hole temperature gradients ($\geq 60^{\circ}\text{C/km}$) of wells, or by anomalous actual temperatures ($\geq 40^{\circ}\text{C}$) of thermal springs.

Figure 7-35. Sites in southwestern New Mexico characterized by anomalous SiO_2 , Na-K-Ca, and Na-K-Ca (Mg corrected) geotemperatures of springs and wells.

data are defined as sites that have SiO_2 geotemperatures 90°C or above and Na-K-Ca geotemperatures greater than or equal to 120°C or the locations that have SiO_2 geotemperatures 90°C or above and Na-K-Ca (Mg corrected) geotemperatures greater than or equal to 70°C . Sites with Na-K-Ca geotemperatures 200°C or above have been added to the latter group in order to increase the data base since Mg corrections were not available for approximately one-half of the Na-K-Ca geothermometry data. Only the data points with Na-K-Ca geotemperatures greater than or equal to 200°C were used in order to prevent the data from being biased by Mg-rich geothermal fluids because, even after the application of the Mg correction, these waters would probably still indicate low to intermediate geothermal reservoir base temperatures.

Figure 7-36 shows a final reduction of the anomalous data and is a composite of Figures 7-34 and 7-35. Figure 7-36 includes: (1) those sites from Figure 7-34 that have both actual well temperatures 30°C or above and bottom-hole temperature gradients greater than or equal to $60^\circ\text{C}/\text{km}$ or thermal springs with temperatures 40°C or above; and (2) those sites from Figure 7-35 which have SiO_2 geotemperatures 90°C or above and Na-K-Ca (Mg corrected) geotemperatures greater than or equal to 70°C or have SiO_2 geotemperatures 90°C or above and Na-K-Ca geotemperatures greater than or equal to 200°C . The locations in Figure 7-36 indicated by solid and open circles simultaneously (i.e., conditions (1) and (2) above are both satisfied) are low to intermediate temperature geothermal resource areas. Over-laying Figure 7-36 with Figure 7-31 shows a spatial relationship between fault and fracture zones and geothermal resource areas, which suggests that the geothermal reservoirs are fault-controlled hydrothermal systems (Lohse et al. 1981a). Comparison of the data in Figures 7-31 and 7-36 suggests the existence of two major trends:

Figure 7-36. Sites in southwestern New Mexico characterized by anomalous geotemperatures, actual well temperatures, bottom-hole temperature gradients, and thermal spring temperatures.

(1) a NW-SE trend through Grant, Luna, and Dona Ana counties, and (2) a north-northwesterly trend across Dona Ana and Sierra counties. These two trends have been previously noted in Dona Ana County (Lohse et al. 1981a). The northwest trend is also present in the residual Bouguer gravity anomaly map (see Figure 7-33), which suggests that the faulting and fracturing probably extend into the crystalline basement. The north-northwesterly trend does not appear to extend into the crystalline basement, unless this trend is actually a composite of N-S and NW-SE components, because no regional residual gravity gradient appears to coincide with this trend. Late Quaternary faulting and gravity both suggest that this conjecture of combined N-S and NW-SE components may very well be the case.

The lineament study of New Mexico (Lepley 1981) provides additional information on structural trends and zones of weakness in the study area. The results of this study show three major grains or zones of weakness through the area: (1) a NW-SE grain, (2) a NE-SW grain, and (3) a N-S grain. A gravity study by Ramberg et al. (1978) also suggests a NW-SE grain crisscrossed with a NE-SW grain. Even though the NE-SW trends are not readily apparent in Figures 7-31, 7-32, and 7-33, these trends may be recognized easily in Figures 7-34 and 7-36. Comparison of the lineament data of Lepley (1981), the tectonic and gravity data shown in Figures 7-31, 7-32, and 7-33, and the gravity data of Ramberg et al. (1978) with the thermal anomalies shown in Figure 7-34 and the identified potential geothermal areas shown in Figure 7-36 suggests that there is a strong spatial relationship between the intersections of the NW-SE, NE-SW, and N-S zones of weakness and geothermal anomalies.

Temperature Gradient Holes

Four shallow (300-ft) temperature-gradient holes were drilled in the Deming-Faywood area (see Figure 7-37). The determining factor in the selection of the drill sites was the proximity of large potential users near Deming to an area suspected of having low-temperature geothermal potential. The sites of the drill holes are situated on a major NW-SE structural trend identified in Figure 7-36 and were positioned in order to determine if this NW-SE zone of crustal weakness is characterized by hydrothermal activity.

The NW-SE trend is defined by gravity, Pleistocene faulting, and a few areas along its length characterized by anomalous temperature data, including actual temperatures of springs and wells, bottom-hole temperature gradients, and geothermometry. Figure 7-38 displays these data for the area shown in Figure 7-37. The data from the four temperature-gradient holes are also shown in Figure 7-38.

Lithologies and temperature-depth data from the temperature-gradient holes are given in Tables 7-2 and 7-3, respectively. The corresponding heat-flow, temperature-gradient, and thermal-conductivity data are given in Table 7-4. Also included in Table 7-4 is the corresponding data from a well, reported by Reiter et al. (1975), in the immediate vicinity of the four temperature-gradient wells. The heat-flow data are shown in Figure 7-38, along with bottom-hole temperatures and depths. Thermal conductivity values were estimated from drill cuttings using generally accepted values for each stratigraphic unit. These values were adjusted for the pore space medium (air), porosity, and permeability in each stratigraphic unit. Temperature-depth profiles are shown in Figure 7-39.

Figure 7-37. Location map for temperature-gradient holes in the Deming-Faywood area.

RESIDUAL BOUGUER GRAVITY; CONTOUR INTERVAL EQUALS 5 MGALS.

FAULT CUTS LATE PLIOCENE OR PLEISTOCENE DEPOSITS (ABOUT 1-4 M.Y.) BALL AND BAR ON DOWN-THROWN BLOCK.

BOTTOM-HOLE TEMPERATURE GRADIENTS $\geq 80^\circ \text{C/KM}$

ESTIMATED RESERVOIR BASE TEMPERATURE OF 110°C BASED ON SiO_2 GEOTHERMOMETRY.

ACTUAL TEMPERATURES ($^\circ \text{C}$)

< 20

20-30

30-70

238/90/2.8

BOTTOM-HOLE / BOTTOM-HOLE / HEAT FLOW
TEMPERATURE / DEPTH / (HFU)
($^\circ \text{C}$) / (M)

Figure 7-38. Geophysical and geological data for the Deming-Faywood area.

Table 7-2. Lithology of shallow temperature-gradient holes in the Faywood-Deming area.

Well Name: TG-23; location: 32°23.5' latitude, 107°43.7' longitude
(spudded 9/14/81; completed 9/17/81; temperature logged 10/23/81).

<u>Depth (ft)</u>	<u>Lithology</u>
0-10	Top soil with gravel
10-50	Ashflow tuff, medium reddish brown, soft
50-70	Fanglomerate, light gray, hard, minor caliche
70-80	Ashflow tuff, medium reddish brown, soft
80-120	Fanglomerate, brownish gray, minor caliche
120-140	Andesite, light gray, hard, altered feldspar
140-150	Rhyolite, light reddish brown, very hard, lots of chert
150-160	Transition
160-250	Andesite, light gray, hard, massive
250-260	Andesite, light gray, veins of chalcedony, fractured (?), red coating (?), possibly hemetitic dust
260-300	Andesite, light gray, hard, massive

Well Name: TG-59; location: 32°21.3' latitude, 107°38.5' longitude
(spudded 9/3/81; completed 9/8/81; temperature logged: 10/23/81).

<u>Depth (ft)</u>	<u>Lithology</u>
0-10	Topsoil
10-150	Rhyolite, pinkish gray, hard, massive, minor caliche (top 10 to 20 feet weathered, chemically altered or weakened)
150-230	Andesite, light to medium gray, hard, minor calcite, chalcedony in fractures
230-275	Andesite, black, very hard, massive

Well Name: TG-60; location: 32°22.0' latitude, 107°40.2' longitude
(spudded 9/9/81; completed 9/11/81; temperature logged 10/23/81).

<u>Depth (ft)</u>	<u>Lithology</u>
0-10	Topsoil
10-20	Rhyolite, light gray, soft, extremely weathered, feldspar altered to kaolinite
20-50	Rhyolitic gravels, light pink, conglomerate (?)
50-70	Rhyolite, light gray, very hard, massive
70-80	Rhyolite, light pink, hard, massive
80-110	Rhyolite, light gray, very hard, massive
110-300	Rhyolite, light pink, hard, massive

Table 7-2. (continued).

Well Name: TG-61; location: 32°24.5' latitude, 107°44.6' longitude
(spudded 9/13/81; completed 9/14/81; temperature logged 10/23/81).

<u>Depth (ft)</u>	<u>Lithology</u>
0-10	Topsoil
10-20	Gravel and sand, assorted volcanic rock fragments
20-40	Ashflow tuff, light brown-gray, semi-soft
40-80	Pebbles, assorted volcanic rock fragments
80-100	Welded ashflow tuff, medium gray, hard
100-120	Andesite, chalcedony, ashflow welded tuff, and rhyolite volcanic fragments
120-140	Andesite, light gray, rotten, almost clay
140-150	Andesite, light gray, hard, massive
150-160	Clay, light brown-gray, soft, sticky
160-170	Granite, whitish pink, hard, contains quartz, feldspar and biotite
170-180	Transition
180-200	Welded ashflow tuff, medium gray, hard
200-280	Welded ashflow tuff, very light gray and reddish brown, minor clays, trace of very weak limestone
280-290	Andesite, light gray, very hard
290-300	Welded ashflow tuff (same as 200 to 280 ft interval)

Table 7-3. Temperature-depth data for shallow temperature-gradient holes in the Faywood-Deming area.

Depth (m)	<u>Well Name and Temperature (°C)</u>			
	TG-23	TG-59	TG-60	TG-61
0				
5	22.13	21.83	22.62	21.84
10	20.99	20.86	21.02	20.72
15	21.09	21.12	21.18	20.88
20	21.41	21.36	21.37	21.16
25	21.66	21.65	21.55	21.40
30	21.87	21.86	21.77	21.61
35	22.13	22.10	21.96	21.84
40	22.41	22.35	22.23	22.07
45	22.65	22.55	22.47	22.25
50	22.85	22.83	22.75	22.50
55	23.05	23.08	22.99	22.69
60	23.27	23.31	23.24	22.86
65	23.51	23.55	23.50	23.04
70	23.75	23.76	23.78	23.16
75	23.99	23.95	24.02	23.29
80	24.21	24.24	24.24	23.48
85	24.45	24.36*	24.54	23.64
90	24.68		24.69	23.83

*The data are measured at a depth of 84 meters.

Table 7-4. Temperature-gradient, thermal-conductivity, and heat-flow data for shallow temperature-gradient holes in the Faywood-Deming area.

Well Name	Location Latitude Longitude		Depth Interval (m)	Temperature Gradient (°C/km)	Thermal Conductivity (10 ⁻³ cal/°C-cm-sec)	Heat Flow ₂ (μcal/cm ² -sec)	Best Heat Flow Value (μcal/cm ² -sec)
TG-23	32°23.5'	107°43.7'	15-40	52.8	7.0	3.7	3.6
			40-90	45.4	7.5	3.4	
TG-59	32°21.3'	107°38.5'	10-45	48.3	7.5	3.6	3.6
			45-80	48.3	7.5	3.6	
TG-60	32°22.0'	107°40.2'	15-35	39.0	8.0	3.1	3.5
			35-85	51.6	7.5	3.9	
TG-61	32°24.5'	107°44.6'	15-25	52.0	5.5	2.9	2.8
			25-50	44.0	7.0	3.1	
			50-90	33.3	7.5	2.5	
Existing Well*	32°22'	107°40'	30-320	83.64±0.31	11.57±0.55	9.68	9.7

*The data are from Reiter et al. (1975). The thermal conductivity is a measured value from 11 core samples.

Figure 7-39. Temperature-depth profiles of the four temperature-gradient holes in the Deming-Faywood area.

Drilling was accomplished using a down-hole hammer and air. Drilling was slow in all holes with drilling rates of only a few feet per hour being quite common, especially when drilling through andesite and rhyolite formations.

Elevated near surface temperatures were not encountered and temperature gradients are near normal ($\sim 40^{\circ}\text{C}/\text{km}$) for the region. However, because of the presence of unusually high thermal conductivities, the heat-flow values are above normal (~ 2.5 HFU), possibly indicating the existence of some type of fault-controlled hydrothermal system at depth or, alternatively, hot dry rock at considerable depth.

Conclusions

Gravity, fault, anomalous actual temperature, bottom-hole temperature-gradient, geothermometry, and lineament data suggest major NW-SE and N-S trends of structural weakness and control throughout southwestern New Mexico. These two trends intersect in the general area of Dona Ana County and appear to be crisscrossed and intersected by secondary zones of weakness that trend in a NE-SW direction. Anomalous actual temperature, bottom-hole temperature-gradient, and geothermometry data suggest that there is a spatial relationship between points of intersections of these trends and potential geothermal anomalies. A spatial relationship between faults and potential geothermal anomalies suggests that the hydrothermal systems are fault controlled. Geophysical data acquired from four temperature-gradient holes indicate that only parts of the NW-SE trends may be associated with hydrothermal activity. These trends do not appear to be characterized by nearly continuous hydrothermal activity and elevated near-surface temperatures as does as apparent NNW-SSE trend, which is believed to be composed of N-S and

NW-SE components. Late Quaternary faulting is generally in a N-S direction; however, when pre-existing NW-SE fracture zones are intercepted, the Quaternary faulting has a tendency to propagate in a NW-SE direction. These late Quaternary faults appear to be associated with nearly continuous hydrothermal activity. This observation, coupled with the observation that Quaternary volcanism appears to have a spatial and temporal relationship with Quaternary N-S faulting, suggests that the N-S trending features are probably of a tensional nature and that the volcanism and faulting are likely to have had a cause-effect relationship.

References

- Aldrich, M. J., Jr., and Laughlin, A. W., 1981, Location, age, and rock type of volcanic rocks younger than 5 million years old in Arizona and New Mexico: Los Alamos National Laboratory, Report LA - 8820-MS, 21 pp.
- Aiken, C., Laughlin, A. W., and West, F. G., 1978, Residual Bouguer gravity anomaly map of New Mexico: Los Alamos National Laboratory, scale 1:500,000.
- Callender, J. R., and Seager, W. R., 1980, Quaternary and late Pliocene geology, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1979: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 6/1 - 6/4.
- Chaturvedi, L., 1980, Geothermal hydrology, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1979: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 8/1 - 8/22.
- Cordell, L., Keller, G. R., and Hildenbrand, T. G., 1978, Complete Bouguer gravity anomaly map of the Rio Grande Rift: U.S. Geological Survey, unpublished map, scale 1:1,000,000.
- Jodry, D., 1981, personal communication, Private Consultant.
- Lepley, L. K., 1981, Lineament map of the State of New Mexico, in Icerman, L., and Starkey, A., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1981: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 4/1 - 4/20 (In Press).
- Lohse, R. L., 1980, Thermal gradients, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1978: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 5/1 - 5/36.
- Lohse, R. L., 1981, Collection of existing water well data in the southern Rio Grande Rift and southwestern New Mexico, in Icerman, L., and Starkey, A., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1981: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 5/1 - 5/20 (In Press).
- Lohse, R. L., Morgan, P., and Swanberg, C. A., 1981a, A heat-flow study of Dona Ana County, southern Rio Grande Rift, New Mexico, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1980: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 5/1 - 5/40.

- Lohse, R. L., Morgan, P., and Swanberg, C. A., 1981b, Preliminary heat-flow assessment of southeast Luna County, New Mexico, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1980: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 5/41 - 5/48.
- Morgan, P., Swanberg, C. A., and Lohse, R. L., 1980, Borehole temperature studies of the Las Alturas geothermal anomaly, New Mexico, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1979: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 9/1 - 9/14.
- Ramberg, I. B., Cook, F. A., and Smithson, S. B., 1978, Structure of the Rio Grande Rift in southern New Mexico and west Texas based on gravity interpretation: Geological Society of America, Bulletin, v. 89, p. 107-123.
- Reiter, M., Edwards, C. L., Hartman, H., and Wiedman, C., 1975, Terrestrial heat flow along the Rio Grande Rift, New Mexico and southern Colorado: Geological Society of America, Bulletin, v. 86, p. 811-818.
- Seager, W. R., 1981, Geology of Organ Mountains and southern San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 36, 97 pp.
- Seager, W. R., Shafiquallah, M., and Clemons, R. E., 1981, Active fault analysis and radiometric dating of young basalts in southern New Mexico, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1980: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 6/1 - 6/12.
- Swanberg, C. A., 1980a, Estimated subsurface temperatures, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1979: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 1/1 - 1/17.
- Swanberg, C. A., 1980b, Catalogue of thermal waters, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1979: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 2/1 - 2/4.
- Swanberg, C. A., 1980c, Water quality of geothermal waters, in Icerman, L., Starkey, A., and Trentman, N., eds., State-coupled low temperature geothermal resource assessment program, fiscal year 1979: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, p. 2/5 - 2/38.
- Swanberg, C. A., 1980d, personal communication, New Mexico State University.

Chapter 8

Hydrologic Study of the Animas Valley - Lightning Dock

KGRA Areas*

Introduction

The Animas Valley is located in Hidalgo County in southwestern New Mexico. Since the area was developed for irrigated agriculture in the 1940's, groundwater levels have declined significantly. Due to the presence of hot groundwater at shallow depths, part of the valley was designated as the Lightning Dock Known Geothermal Resource Area (KGRA) by the U.S. Geological Survey. The Lightning Dock geothermal system is one of the areas in New Mexico with indicated subsurface temperatures exceeding 150°C (White and Williams 1975). In the last several years there have been a number of recent geomorphologic, geochemical, geophysical, and geological studies of the area. Earlier studies of the hydrology in the Animas Valley by Schwennesen (1918) and Reeder (1957) provide valuable baseline data for the valley, but these studies need to be updated in light of the more recent geothermal investigations.

The objectives of this study are to update the hydrogeothermal data base in the Lightning Dock KGRA and to apply a computer model for studying the general hydrologic behavior of the shallow aquifer system. A calibrated computer model may provide information on aquifer transmissivity, storage, and boundary conditions, which is necessary for the development of heat or solute transport models for the geothermal system. Application of the computer model

*The principal authors of Chapter 8 are Mr. David B. Hawkins, Research Assistant and Dr. Daniel B. Stephens, Assistant Professor of Hydrology, Department of Geoscience, New Mexico Institute of Mining and Technology.

is also intended to point out areas where future data collection and research are needed.

A secondary objective of this study is to determine the feasibility of applying the kriging technique to the calibration of a steady-state aquifer flow model. A somewhat similar approach was taken by Binsariti (1980) in modeling a groundwater system in southern Arizona, but other examples of applying the kriging technique to aquifer modeling are rare.

Characteristics of the Animas Valley

Location

The Animas Valley may be partitioned geographically into the upper Animas Valley in the south and lower Animas Valley in the north. The principal area of interest for this study is the lower Animas Valley (see Figures 8-1 and 8-2). Included in this portion of the valley are the hot wells which tap the geothermal system and the area of principal irrigation development. The study area for the computer simulation is bounded approximately by Interstate Highway 10 on the north (approximately the northern boundary of Township 24 S.), the line between Township 27 S. and 28 S. on the south (approximately 3 miles south of the town of Animas), the Pyramid Mountains on the east, the Peloncillo Mountains on the west.

Climate and Vegetation

The climate of the lower Animas Valley is mild and semiarid. The weather station at Animas (elevation 4415 ft) reports an average annual precipitation of 10.76 inches over a 45-year period of record (Gabin and Lesperance 1977).

Figure 8-2. Lower Animas Valley-Lightning Dock KGRA study area.

The mean annual temperature is 60.1°F and the mean Class-A pan evaporation is 101.6 in. On the average, there are 187 frost-free days, from April 24 to October 28 (Blaney and Hanson 1965). Approximately 55% of the average annual precipitation falls during July, August, and September, principally in the form of brief but intense afternoon thunderstorms. During the summer months the potential evapotranspiration rate is near the annual maximum. The lowest quarterly precipitation occurs in November, December, and January, in the form of gentle, but more sustained rainfall. During this period the potential for evapotranspiration is at a minimum.

Precipitation in the higher elevations east and west of the valley and south into the upper Animas Valley may be somewhat greater than that measured at Animas. The Cloverdale Ranger Station located at an elevation of 5400 ft along the western flank of the upper Animas Valley received an average annual precipitation of 22.53 inches for a nine-year period of record (Gabin and Lesperance 1977). Eick's Ranch, located in the upper Animas Valley (5300 feet above sea level), receives an average of 15.26 inches of precipitation annually. In contrast, Road Forks, located in the northwest part of the study area at 4195 ft above sea level, receives on the average only 6.92 inches of precipitation.

The natural vegetation of the valley may be classified as semidesert shrub and semidesert grass. The shrub type vegetation consists mainly of creosote bush, blackbrush, and mesquite. The grasses include black grama, dropseed, and bush muhly.

Topography and Drainage

The topographic and geomorphic setting of the Animas Valley is described in considerable detail by Schwennesen (1918) and Fleischhauer (1977). The Animas Valley is a closed drainage basin, which stretches for 60 to 70 miles

in a north-south direction and varies in width from six miles in the south to 11 miles in the north. It is bounded on the southeast by the Animas Mountains which attain an elevation of over 8000 ft. The lower Animas Valley is bounded on the east by the Pyramid Mountains and on the west by the Peloncillo Mountains. Both of these ranges attain elevations of 5000 to 6000 ft. The San Luis Valley lies south of upper Animas Valley and is separated from it by a low topographic divide. The north end of the lower Animas Valley is separated from the Gila River drainage by a broad table and near Summit, New Mexico (see Figure 8-1).

The upper Animas Valley is drained by Animas Creek, which is a moderately incised, northward-flowing ephemeral drainage that has formed a narrow floodplain bordered by low bluffs. The heads of most of the tributaries to Animas Creek are in the Peloncillo Mountains to the west. The Animas Creek floodplain broadens northward until it loses definition about five miles south of Animas, where the valley broadens and becomes flatter. The point where the channel of Animas Creek becomes poorly defined marks the approximate boundary between the upper and lower Animas Valley.

The lower Animas Valley is composed of a broad, flat central plain bordered by coalescing alluvial fans which slope toward the center line axis of the valley. Surface runoff from the upper Animas Valley may infrequently reach the lower Animas Valley. Three playas, South Alkali Flat, Hackberry Lake, and North Alkali Flat, are located at the lowest elevations of the central plain northeast of Road Forks. These playas are the remnants of a much larger lake which existed during late Wisconsinan to middle Holocene time (Fleischhauer 1977). Because the lower Animas Valley is a closed surface-drainage basin, water collects in these playas during the rainy season and may remain there for as long as several months.

The Lordsburg Draw drains Lordsburg Valley which is located northeast of the lower Animas Valley. This ephemeral drainage enters the northeast side of South Alkali Flat in the lower Animas Valley and occasionally discharges to the playa.

Geothermal Anomaly

Prior to 1948 there was no reported surficial expression of a geothermal resource. In that year, several wells drilled at location 25.19.7.234 (see Appendix A for well numbering system) struck steam and boiling water at a depth of 88 ft. Hot water for heating greenhouses is currently produced from shallow depths in a relatively small area which has perhaps a 1000-ft radius. However, Logsdon (1981) noted that the presence of hot-spring deposits on both sides of the valley and low-temperature hydrothermal deposits such as fluorite, psilomelane, calcite, and opaline silica occur in veins in the western Pyramid Mountains. Kintzinger (1956) attempted to delineate the plume of hot water by measuring soil temperatures at a depth of one meter. Strangway and Holmer (1966) noted the geothermal anomaly in an airborne infrared survey of the area made from a flight, which was conducted at an average terrain clearance of 3000 ft. Summers (1976) presented data on temperature profiles in wells in and near the geothermal anomaly. Two wells in 25.19.7.234 show bottom-hole temperatures of 216°F at depths of 80 to 100 ft (Summers 1976).

Geology

Studies by Deal et al. (1978) and Elston et al. (1979) indicate that the Pyramid Mountains are a complex of mid-Tertiary volcanic rocks, most of which are part of the Muir Cauldron that is an Oligocene ash-flow tuff eruptive

center. These studies suggest that the collapse of the Muir Cauldron caused the formation of a ring fracture zone which intersects the area of the hot wells. Subsequent to the Oligocene volcanism, north-south trending Basin and Range faults formed a graben between the present locations of the Pyramid and Peloncillo mountains. The eastern fault presumably extends through the area of the hot wells.

Elston et al. (1979) propose that the intersection of the Basin and Range fault zone with the ring fracture zone of the Muir Cauldron formed a zone of sufficiently high permeability to allow geothermal fluids to flow from greater depths.

The trough formed by Basin and Range faulting was filled with sediments derived mostly from the mountain blocks and deposited by the ancestral Animas Creek and Lake Animas during the Tertiary Period. Fleischhauer (1977) dealt extensively with the geomorphology of the deposits relating to ancient Lake Animas. According to Fleischhauer (1977), the sediments of the valley flat consist of fine-grained sand, silt, and clay which represent playa sediments. Gravel is found at shallow depths and at various places and was probably deposited by the former delta of the ancestral Animas Creek. In some places, buried stream channels are marked by vegetation belts. The alluvial fan complexes which border the central valley consist of gravel, sand, silt, and some clay. Studies by the New Mexico Bureau of Mines and Mineral Resources are in progress to decipher the complex depositional history of the basin.

Fleischhauer (1977) has noted evidence for recent faulting in the area of the hot wells, which has displaced relatively recent alluvial-fan surfaces. For example, just north of the hot wells, fault scarps which display three

feet or more of vertical offset were found (Fleischhauer 1977). The presence of the fault scarp in this unconsolidated material indicates that the faulting is probably quite recent.

Due to the rather complex structural history of the area, the thickness of the alluvium is quite variable. The depth to bedrock at two wells in 25.19.7.234, near the hot wells, is about 85 ft (Reeder 1957). The bedrock encountered in these wells consists of silicified rhyolitic welded tuff (Summers 1976). A deep oil test well (Cockrell Corporation, Number 1 Federal-Pyramid) was drilled approximately two miles north of the hot wells at location 24.19.31.23. The log of this well is as follows (Summers 1976):

<u>Depth (ft)</u>			<u>Description</u>
0	to	1890	Valley fill
1890	to	5795	Volcanics
5795	to	7130	Paleozoic rocks
7130	to	7394	Precambrian rocks

A borehole for measuring heat flow was drilled to a depth of 985 ft by Chevron Resources Company near the lava flow northwest of Animas in 27.20.1. According to Smith (1978), this hole was drilled entirely in clayey and gravelly sands and neither high fluid temperature nor anomalous thermal gradients were encountered.

Figure 8-3 shows a gravity survey conducted by Preslar as reported in Smith (1978). The high gravity gradients along the sides of the valley are indicative of the high-angle nature of the Basin and Range faulting. There appears to be a constriction of the valley fill in the area to the south of Cotton City. Also of interest is the ridge of elevated gravity measurements,

Figure 8-3. Complete Bouguer gravity anomaly map [gravimetry by Preslar, in Smith (1978)].

which extends from just north of Table Top Mountain to the area of the hot wells. The shallow depth to bedrock (about 85 ft) at the hot wells supports the interpretation that the gravity high represents a shallow buried bedrock ridge.

Another geological feature which may be related to the hydrogeothermal system is the Quaternary basalt flow located several miles west of the town of Animas. This flow was dated at 140,000 years B. P. by Marvin et al. (1978). Based on geophysical evidence and chemical constituents in shallow groundwater, Logsdon (1981) proposed that a northeast-southwest trending fault, downthrown to the northwest, extends from the basaltic flow area across the valley and intercepts the Basin and Range and ring-fracture faults at the hot wells. Logsdon (1981) postulates that this fault provides an avenue for the leakage of geothermal fluids into the valley fill from depth. This leakage is most pronounced at the hot wells where several fracture zones intersect.

Hydrogeology

The aquifer in the lower Animas Valley consists of lenses of gravel, sand, silt, and clay of varying degrees of consolidation and sorting. These deposits are related to the ancestral Animas Creek, ancient Lake Animas, and coalescing piedmont gravel terraces along the sides of the valley. Consequently, the aquifer material is quite heterogeneous and individual lenses are difficult to trace over wide areas. Because of the presence of clay lenses, the groundwater may be under confined conditions locally, but overall the groundwater may be considered to be under unconfined conditions (Reeder 1957).

In general, the direction of groundwater flow is northward from the U.S.-Mexico border along the axis of the upper and lower valleys. Where recharge occurs along the mountain fronts, groundwater flows generally toward the center of the valley. However, there is little water-level data available along the mountain fronts. Although the basin is closed with respect to surface runoff, Reeder (1957) suggests that the groundwater basin is not closed because the groundwater discharges from the lower Animas Valley to the Gila River.

Perched water-table conditions exist in the upper Animas Valley and little is known about underlying aquifers in this area. Presumably, groundwater from the perched aquifer leaks downward and recharges the underlying main water-table aquifer. The zone of the perched water extends north to a point about four or five miles south of the town of Animas. From that point north to the line separating Townships 27 S. and 26 S., the water-table gradient was approximately 5.8 ft/mi (Reeder 1957) prior to extensive irrigation. The water-table gradient for the next six miles north was somewhat steeper (i.e., 10.6 ft/mi), which may indicate a zone of lower transmissivity or possibly a constriction of the aquifer in the subsurface. From the line separating Township 26 S. from Township 25 S., the water table sloped to the north at an average gradient of 4.9 ft/mi.

Before irrigation development was initiated in the valley, flow in the aquifer was at a steady state. There was practically no net change in water levels over an extended period of time. Some windmills pumped groundwater for domestic or stock purposes but the total withdrawals were negligible. Only four irrigation wells were drilled in Township 26 S., Range 20 W. prior to 1948. In the spring of 1948, large-scale irrigation development in the valley was initiated. This development was centered in the Cotton City area. The

use of groundwater for large-scale irrigation purposes continued so that by January 1955, the maximum water-table decline was almost 30 ft. Reeder (1957) estimated that, by that time over a 120 square-mile area, the water level had declined more than 5 ft.

The New Mexico State Engineer's Office recognized the need for an investigation of the hydrology of the valley at the onset of the irrigation development. In May 1948, the State Engineer defined an area of 205 square miles as the Animas Valley Underground Water Basin, which was then closed to further groundwater appropriation in June of that year. Because of the possibility of increased irrigation development south of the town of Animas, the State Engineer extended the declared basin south to the U.S.-Mexico border in February 1956. This extension increased the area of the declared basin by 221 square miles (Reeder 1957, Figure 39). The State Engineer has monitored the water levels and pumpage in the declared portions of the valley since 1948.

Hydrologic Computer Modeling

Model Calibration

Model calibration is a process of adjusting input parameters, such as transmissivity, storage, recharge, and discharge, until the predicted output of hydraulic head or water-level elevations satisfactorily matches the hydraulic head measured in the field. A trial-and-error approach was used in combination with empirical input parameter data. To reduce the number of adjustable parameters, the calibration for transmissivity and the associated boundary conditions were based primarily on conditions prior to extensive irrigation, that is, for steady-state groundwater flow conditions.

The general approach for calibration is to start with field-measured hydraulic head data. Equal-head values may be contoured by best-fit-by-inspection interpolation or by one of several linear interpolation schemes. One such scheme, the kriging technique, is an exact interpolator which has the advantage that the procedure gives estimates of the errors associated with the interpolation process. Specific-capacity measurements and pumping tests provide information on aquifer transmissivity for the basin. Transmissivity values may also be contoured by hand or by the kriging technique. This distribution of transmissivity is used in the computer model as a first guess of the real distribution. The initial hydraulic-head data and estimates of recharge and discharge conditions are also inputs to the model. The model is run to steady state and the predicted hydraulic-head output is compared with the input hydraulic head. The input parameters, mostly transmissivity values, are adjusted and the model is allowed to again run to steady state. This process continues until a reasonable agreement between measured and predicted hydraulic-head values occurs.

Storage coefficients and pumping-rate distributions are obtained by trial-and-error calibration for a time period covering the first few years of irrigation development. The initial guesses for these values are based on aquifer pumping rests, well locations, and published information on cropping and water use. The trial-and-error procedure is again used until a satisfactory match in hydraulic-head values is observed. When such a satisfactory match is obtained, the model is considered to be calibrated and the input parameters are fixed for further runs.

Model verification is achieved by running the calibrated model for several years after the transient calibration period. During the verification process, aquifer properties are held constant and the model is

run with best estimates of pumping rates for the period. A good agreement between the predicted and observed water-level draw down tends to verify that the aquifer properties are reasonable estimates.

Application of Kriging Technique Results to Model Calibration

The first phase in the modeling of the groundwater flow system in the lower Animas Valley was the application of the kriging technique to the distribution of hydraulic head and transmissivity in the valley. The principal results of this phase of research (see Figures 8-4, 8-5, 8-6, and 8-7) are contour maps of the predicted values and standard deviations of prediction errors of the steady-state head distribution and the distribution of the natural log of transmissivity (Hawkins 1981).

The second phase in the development of a model of the steady-state flow system is an analysis of the flow system making use of a flow net. Ideally, this analysis would be straightforward, that is, streamlines would be drawn in the head map generated by the kriging technique. The $\ln T$ map, also generated by the kriging technique, would then be superimposed on the flow net and values for flux within individual stream tubes could then be calculated by:

$$Q = Tiw, \quad (1)$$

where Q is the flow rate ($L^3 T^{-1}$), T is transmissivity ($L^2 T^{-1}$), i is the hydraulic gradient (dimensionless), and w is the width of the flow path (L^1).

A number of phenomena affect the recharge-discharge relationships in the valley if the head map generated by the kriging technique is correct (see Figure 8-4). There appears to be a significant recharge mound at the southern margin of the map. This recharge appears to flow east into the Playas Valley,

Figure 8-4. Water-level (hydraulic head) contours predicted by the kriging technique (elevations in ft above mean sea level).

Figure 8-5. Distribution of standard deviations of error for the hydraulic head predicted by the kriging technique.

Figure 8-6. Natural logarithm of transmissivity predicted by the kriging technique.

Figure 8-7. Distribution of standard deviations of error for the natural logarithm of transmissivity predicted by the kriging technique.

north along the axis of the lower Animas Valley, and west into the Peloncillo Mountains. There also appears to be recharge from the northwestern margin of the map, possibly from the Peloncillo Mountains. Some recharge is evident along the northeastern margin of the valley, which could be due to recharge from the various ephemeral drainages that issue from the northwestern Pyramid Mountains. A center of discharge is located at the northcentral margin of the map and the entire flux in the valley appears to be discharging there.

Based on the available hydrologic knowledge of the lower Animas Valley, it is evident that some of the phenomena represented on the head map do not actually exist (see Figure 8-4). There are no hydrogeological conditions which would create a recharge mound at the southern margin of the map, and this apparent phenomenon is probably the result of a lack of data points in the southwest portion of the area and an anomalous head value in the southeast corner of the map. The anomalously-low water-level data point in the southeast may be related to interflow between the lower Animas Valley and the Playas Valley to the east.

Comparison of predicted head values on the southeast portion of the map with head values reported in Doty (1960) for the northwest portion of the Playas Valley seems to suggest that there is a slight head gradient and underflow from the Animas Valley eastward into the Playas Valley. The subsurface geology of the area between the northernmost extent of the Animas Mountains and the southern tip of the Pyramid Mountains shows that outcrops of consolidated Tertiary volcanics and Paleozoic sediments occur in the gap between the Animas and Pyramid mountains (Deal and Elston, in preparation). Maps produced by Deal and Elston (in preparation) suggest that block faulting displaced the consolidated rocks upward and bedrock may occur quite near the surface throughout the gap. If this interpretation is true, the two basins

may be separated by a low permeable boundary in the subsurface and, consequently, there may be evidence for considering the groundwater-flow systems in the lower Animas and Playas valleys to be hydrogeologically separate. Further hydrogeological and geochemical studies are necessary to determine the possibility of a definite hydrologic communication between the two valleys. In the current study, the final version of the flow net was adjusted so that no flow would occur across the gap between the Animas and Pyramid mountains.

The head map also indicated areas of mountain-front recharge. The maps of standard deviation of prediction errors of both head and $\ln T$ (see Figures 8-5 and 8-7) show that those areas where mountain-front recharge is supposedly occurring are the areas where the standard deviation of error is relatively high. In other words, uncertainty in these parameters is high at the valley margins because of the lack of input data.

Yakowitz and Duckstein (1980) pointed out some of the difficulties associated with excessive initial head errors in this type of computer modeling. The model produced in such circumstances may be inherently unstable because of the ill-posed nature of the problem. It appears from other studies (Wilson et al. 1980) that mountain-front recharge is a particularly hard problem to deal with in a quantitative sense. In fact, Wilson et al. (1980) suggest that, faced with a lack of definitive data in dealing with mountain-front recharge,

"the modeler can arbitrarily define a regional aquifer boundary that more than likely is inside the real regional aquifer boundary. In being conservative about the placement of this boundary, nothing will be lost except the uncertainty associated with trying to model the data between this boundary and the mountain mass."

This recommendation was adhered to in dealing with the western margin of the basin. However, the eastern margin presented a unique problem. The localized expression of thermal waters in the valley (25.19.7.234) is centered near the eastern margin of the basin. Thus, in order to include the geothermal area in the model, it was necessary to include the effects of what may be termed mountain-front recharge along approximately one-third of the eastern margin of the valley, even in the absence of sufficient empirical data.

The apparent discharge area at the northern margin of the study area is also located in an area of fairly high uncertainty in head prediction. It is possible that some discharge occurred here under steady-state conditions due to evaporation because the depth to water was less than 20 ft in that area in 1948 (Reeder 1957). However, the amount of discharge that occurred, if any, was probably relatively small and the principal discharge area prior to extensive irrigation was the Gila River (Reeder 1957, Plate 4). In addition, the configuration of the contours of the standard deviation of error (see Figure 8-5) suggests that the occurrence of the discharge area is probably an effect induced by lack of data around the margin of the study area.

Flow-Net Construction

The final version of the flow-net construction (see Figure 8-8) was a product of both the kriging technique and hydrologic intuition. In the final version, the solid contours were predicted by the kriging technique and the dotted contours were adjustments made in the head contours generated by the kriging technique. It may be argued that, in view of the alterations, the application of the kriging technique to the hydraulic heads was not particularly useful. However, the kriging technique did provide estimates of the prediction errors which were useful in the construction of the flow net.

Implicit in a flow-net analysis of this type is the assumption that there is no recharge occurring along a streamtube. In other words, variations in the width of an individual streamtube are due to variations in transmissivity and head gradient and not variations in flux. Reeder (1957) noted that none of the available hydrographs of wells in the lower Animas Valley appeared to respond directly to recharge by local precipitation and that little, if any, of the precipitation on the valley plain percolated to the water table. Data collected for the town of Animas (Gabin and Lesperance 1977) indicated an average annual precipitation of 10.76 inches (45 years of record) and a Class-A pan evaporation of 101.60 inches (3 years of record). Thus, it is reasonable to assume that a very minor amount of recharge occurred in the center of the valley under pre-irrigation conditions.

Another assumption implicit in this flow-net analysis is that transmissivity is isotropic, that is, transmissivity is considered to be independent of the direction of measurement. The assumption of isotropic transmissivity in the horizontal plane may be reasonable in horizontally-stratified sediments.

The boundary conditions for the flow net indicate that groundwater flow in the main portion of the lower Animas Valley is derived principally from northward underflow from the upper Animas Valley. Conditions in the upper Animas Valley are more favorable for groundwater recharge than in the lower Animas Valley because of the slightly greater precipitation in upper Animas Valley and the channelization of runoff into Animas Creek.

Infiltration along Animas Creek apparently forms a zone of shallow perched water in the young poorly-consolidated alluvium (Schwennesen 1918; Reeder 1957). This young alluvium overlies less permeable, more consolidated alluvium (Gila Conglomerate?). The perched water table extends north to

approximately the middle of Township 28 S. and its northernmost extent coincides approximately with the point at which the channel of Animas Creek loses definition (Reeder 1957, Plate 4). Lack of well data prevents the precise location of the main body of the saturated zone, which may lie at some depth below the perched zone. Percolation from the perched zone to the main water table is probably responsible for most of the recharge to the main water-table aquifer in the upper Animas Valley. The details of the relationship between the perched water table and the main body of saturation are unknown at this time and further research on this problem is needed in order to better quantify the recharge to the lower Animas Valley.

Figure 8-8 indicates that groundwater flow enters the east side of the valley along the southwestern margin of the Pyramid Mountains. Several drainages, notably, Pinkey Wright Canyon, Holtkamp Canyon, Rainbow Canyon, and Woodhaul Canyon, drain into the lower Animas Valley from the Pyramid Mountains in this area.

In order to solve the steady-state flow equation, it is necessary to obtain estimates of values for transmissivity as well as to quantify the fluxes in and out of the valley. Thus, the $\ln T$ map and the associated standard deviation of error (see Figures 8-6 and 8-7) were superimposed over the final version of the flow net shown in Figure 8-8. By inspecting each streamtube, the block (i.e., head-gradient interval) within a particular streamtube which had the lowest standard deviation of error was identified. The average transmissivity in that block was then calculated by:

$$\mu_w = \exp \left(\mu_v + \frac{\sigma_v^2}{2} \right), \quad (2)$$

where μ_w is the expected value of T , μ_v is the expected value of $\ln T$, and

Figure 8-8. Steady-state flow net.

σ_v is the variance of $\ln T$. This equation is a transformation such that the entire right side of the equation has dimensions of $L^2 T^{-1}$. The variance of $\ln T$ for that particular block, as determined from Figure 8-7, was used to approximate σ_v^2 . Equation (2) was applied to a subregion of the total domain so that μ_v represented the average of the prediction by the kriging technique in that block of the streamtube.

The transmissivity for one block in each streamtube was determined by the above process. The block chosen was the block in which there was the most confidence in the predicted value of $\ln T$. Using this value for transmissivity and the assumption that the flux within a streamtube was constant, values for flux and transmissivity were computed from Eq. (1) for all the streamtubes and all the blocks within the streamtubes.

Based on this analysis, the total flow into the lower Animas Valley from the upper Animas Valley under steady-state conditions is approximately 3170 acre-ft/year. The recharge derived from the southwestern Pyramid Mountains is approximately 1180 acre-ft/year. However, the sum of these numbers, 4350 acre-ft/year, does not necessarily represent the total steady-state flux out of the lower Animas Valley, which would probably be somewhat larger because of recharge that may occur along the eastern margin of the Peloncillo Mountains and the northwestern margin of the Pyramid Mountains. These areas were omitted from the flow-net analysis because of the inherent uncertainty in dealing with mountain-front recharge and because recharge here does not exert a great deal of influence on conditions near the irrigation pumping center and the KGRA. The actual amount of mountain-front recharge occurring in these areas could be significant in the region along the northwest margin of the Pyramid Mountains which may be contributing recharge (i.e., Jose Placencia Canyon, Hampton Canyon, Mansfield Wash, and Gore Canyon). It is possible that

some of the recharge in the Jose Placencia Canyon area is accounted for in the flow net.

Reeder (1957) computed the total flow rate across the 4150-ft water-level contour line to be about 2700 acre-ft/year. The location of this area corresponds closely to the area contained in the flow net (see Figure 8-8). According to our calculations, the value given by Reeder (1957) is low by almost 40%.

In order to determine whether the total recharge for the upper Animas Valley and the southwest side of the Pyramid Mountains is reasonable, a Thiessen polygon analysis of the precipitation occurring over the proposed recharge area was performed. The recharge area was assumed to consist of the area bounded by the continental divide on the east (i.e., the Pyramid and Animas mountains), the drainage divide along the crest of the Peloncillo Mountains on the west, the U.S.-Mexico international boundary on the south, and the middle of Township 24 S. on the north. The flat valley plain of the lower Animas Valley was excluded because no recharge was assumed to take place in this region. Although the San Luis Valley to the south is topographically separated from the upper Animas Valley, the groundwater divide is actually located approximately at the international border. For this reason, the San Luis Valley north of the border was included in the analysis.

Twelve measurement stations (i.e., Cloverdale, Cloverdale Ranger Station, Eick's Ranch, Gray Ranch, Dunagan Ranch, Rodeo, Rodeo Airport, Pratt, Animas, Lordsburg 4 SE, Road Forks, and Culberson Ranch) were included in the precipitation analysis, using data from Gabin and Lesperance (1977). The proposed recharge area totaled 865 square miles. It is likely that more precipitation occurs at the higher elevations than at the lower elevations where the recording stations are located; therefore, this approach should

underestimate precipitation values. The average annual precipitation over the 865-square mile area is 542,700 acre-ft. Thus, the computed flux through the Animas Valley is less than 1% of the total available precipitation, which is well within the limits of a reasonable ratio of recharge to total precipitation in a semiarid southwestern alluvial basin.

In examining the values for transmissivity computed for the flow-net analysis, it is interesting to note the general contrast between values in the southcentral and northcentral portions of Figure 8-8. Transmissivities in many parts of the southcentral area are nearly an order of magnitude less than transmissivities in the northcentral area. This difference could result from either a contrast in hydraulic conductivity or aquifer thickness or some combination of the two.

Smith (1978) presents a map of the complete Bouguer gravity anomaly (see Figure 8-3). According to Smith (1978), the high values of gravity to the south of the Table Top Mountain are uncharacteristic of southwestern alluvial basins, whereas, the steep gravity gradients north of Cotton City are typical of alluvial basin structures in the Basin and Range Province. There also appears to be a ridge of high gravity values extending north from Table Top Mountain to the hot wells (25.19.7.234). The areas south of the hot wells and south and east of Cotton City are probably the expression of an area where rocks more dense than the valley alluvium lie at shallow depths. In fact, analysis of the gravity data (Smith 1978) indicates that more than 2300 ft of valley fill may be expected north of Cotton City, whereas, less than 500 ft of fill may be expected southeast of Cotton City.

These two areas of contrasting valley fill thickness correspond rather closely to the two areas of contrasting transmissivity as determined from the flow-net analysis. In a number of cases, ratios of transmissivity from blocks

in the two contrasting regions are quite similar to the ratios of depths of fill for the two domains. Since transmissivity is the product of hydraulic conductivity and aquifer thickness, aquifer thickness may largely determine the contrast in transmissivities, which would imply that average hydraulic conductivities in the two regions are quite similar.

Model Description

The general two-dimensional groundwater flow equation is

$$\frac{\partial}{\partial x} \left(T \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(T \frac{\partial h}{\partial y} \right) = S \frac{\partial h}{\partial t} + W(x, y, t), \quad (3)$$

where x and y are the Cartesian coordinate axes in the horizontal plane, T is the transmissivity ($L^2 T^{-1}$), h is the hydraulic head (L), S is the storage coefficient (dimensionless), W is a source term (LT^{-1}), and t is time (T). The aquifer is assumed to be isotropic in the horizontal plane and heterogeneous such that the coefficients may vary from point to point. Under steady-state conditions the time derivative of head vanishes.

The U.S. Geological Survey two-dimensional groundwater-flow model (Trescott et al. 1976) was selected for simulating the study area. This program numerically approximates Eq. (3) by a finite-difference technique in which the flow field is divided into a grid system with each grid block being internally homogeneous. A flow equation is written for each block and the resulting system of equations may be solved by either the strongly implicit procedure, the iterative alternating-direction-implicit procedure, or the line-successive-over-relaxation method.

Program options include simulation of flow in an artesian aquifer, a water-table aquifer, or a combined artesian and water-table aquifer. In the

general case, the simulated aquifer may be heterogenous and anisotropic and have irregular boundaries. The source term, $W(x,y,t)$, may include constant recharge, leakage from confining beds in which the effects of storage are included, evapotranspiration, and pumping. Pumping rate is permitted to vary step-wise during the simulation.

Boundary conditions for the grid represent either prescribed head or flux. An impermeable boundary is treated as a zero-flux boundary by assigning zero transmissivity to the block outside the boundary.

The area included in the computer model was the same area included in the flow-net analysis (see Figure 8-8). In order to approximate conditions at the north and south end of the study area so that edge effects would be negligible during the simulation period, it was necessary to expand the grid by several miles to the south and north of the corresponding flow-net boundaries. However, by expanding the grid to the south, the model included the area of the perched aquifer, where water-level elevations are much greater than in the underlying main aquifer. Because no data have been found on the steady-state heads of the main aquifer in this area, initial heads were approximated by extrapolating the head gradient in the main aquifer at the southern margin of the flow net southward into the grid expansion. The extended southern boundary was then treated as a constant-flux boundary using the assumption that pumpage in the main saturated zone would not affect the rate of recharge by percolation from the perched to the main aquifer.

The northern boundary was extended in the same manner by maintaining the head gradient present at the northern margin of the flow net. Pre-irrigation head data in the northern area are also scarce. An additional unknown in this area is the effect of possible recharge from the Lordsburg Draw area. The Lordsburg Draw, an ephemeral stream, drains a considerable area in the

Lordsburg Valley and empties into the northeastern part of the South Alkali Flat. Any recharge from the Lordsburg Draw would occur sufficiently far down gradient of the primary area of interest that its effect on the study area is likely to be negligible. The northern boundary of the extended grid was treated as a constant-head boundary because pumpage during the simulation period should have little effect at this distance from the center of pumpage.

The western boundary of the modeled area was approximated as a no-flow boundary. This boundary was intended to coincide with the westernmost streamline of the flow net. There is little data west of this streamline, and it is possible that the bedrock-alluvium contact is not far west of this streamline. By definition, a streamline represents an impermeable boundary; therefore, this approximation should be reasonable.

The sectors along the eastern margin of the flow net (see Figure 8-8), where the direction of groundwater flow is parallel to the mountain front, were treated as impermeable boundaries. The mountain-front recharge area to the east and southeast of the hot wells was treated as a constant-head boundary. This choice is based on the assumption that water levels along the mountain margins will be affected only slightly by irrigation pumpage.

The flow field was uniformly divided into blocks one mile on a side because the amount of data did not warrant division of the flow field into smaller increments (see Figure 8-9). The grid network was aligned roughly along the axis of the valley but it does not correspond to the township and range system alignment. The computer grid included 197 solution nodes or 197 square miles of simulation area for this block-centered configuration. Column and row numbers are included in Figure 8-9 for reference and the north and south grid extensions are not included since the conditions in those extensions were artificial constructs, whose purpose was to give realistic

CH Constant head node

Figure 8-9. Finite-difference mesh used in the computer simulation.

conditions within the primary area of interest. The grid included six constant-head nodes in the north, seven constant-head nodes in the east, and six constant-flux nodes along the southern margin. Transmissivity values were entered by superimposing the grid over the steady-state flow net and determining an average transmissivity for each computer grid block by inspection.

Steady-State Model Calibration

In order to check the accuracy of this computational procedure, a steady-state computer simulation was run. The total flow rate as computed by the steady-state computer simulation was 571,630 ft³/day, whereas, the flow-net analysis yielded a value of 520,140 ft³/day, a difference of 9%. Some slight modifications were made in transmissivities in order to reproduce the steady-state head distribution as closely as possible. Figure 8-10 shows the steady-state head map as computed by the numerical simulation. Superimposing the data of Figures 8-8 and 8-10 and subtracting the head values at the centers of each block provides a quantitative comparison between the simulated and observed heads.

The differences in heads were then compared to the values of the standard deviation at the centers of the grid blocks generated by the kriging technique. The maximum absolute value of the difference was 8.5 ft in the basalt flow area, 60% of the nodes had errors less than 2 ft, and 66% of the solution nodes had errors which were smaller than $\pm 2\sigma$, where σ is the standard deviation from the Kriging process. These results indicate a reasonable agreement between the flow net and the computer model. In fact, 37% of the nodes where the error was greater than $\pm 2\sigma$ were located in the vicinity of the lava flow in the southwest sector of the study area, where data are relatively sparse.

Figure 8-10. Simulated steady-state water-level elevations from computer model calibrations.

It should be kept in mind that this error analysis is not very rigorous since a comparison was made between the simulation heads and the flow-net heads even though the flow net was derived from a combination of the kriging technique and hydrologic intuition. Therefore, the term error, as used here, does not necessarily represent the difference between the simulation and the actual situation.

Calibration Under Non-Steady Conditions

Calibrating the model for a period when water levels are changing with time requires input parameters of pumping rate and storage coefficient at each grid block. The period selected for the model calibration was April 1948 to January 1955. Prior to April 1948, the aquifer was assumed to be in a condition of steady state. In reality, there was some small amount of irrigation development in the lower Animas Valley prior to April 1948. According to Reeder (1957), Wells 26.20.5.422 and 26.20.4.422 were drilled in 1934 and 1936, respectively, and were used subsequently for irrigation. In addition, Wells 26.20.4.444 and 26.20.8.434 were drilled in 1946 and 1947, respectively, and were pumped for irrigation purposes prior to April 1948. Unfortunately, the State Engineer did not initiate an intensive data collection program on the lower Animas Valley until early in 1948 when large-scale irrigation development began. For this reason, data on amounts of pumpage prior to the 1948 irrigation season are lacking, and it was assumed that the effects of the early irrigation were small, especially in comparison to the pumpage which occurred after April 1948. The small amount of pumpage which occurred prior to 1948 could be a possible source of error in the simulation.

In setting up the problem for transient simulation, it is necessary to assign pumpage rates to particular grid blocks. Personnel from the State Engineer's Office took discharge measurements of 27 selected irrigation wells in September and October 1948. At that time, reports from farmers of hours of operation for particular wells were recorded. Based on the discharge measurements and the estimate of total hours pumped, it was possible to estimate the total pumpage from a specific well for the 1948 irrigation season. These estimates of total hours pumped are subject to fairly large errors (Putnam, personal communication 1981).

According to Reeder (1957), water use for irrigation in 1948 averaged 1.6 acre-ft/acre. This figure may be somewhat in error because many pumps were not in operation for the full pumping season during the first year of operation.

Discharge measurements and estimates of total hours pumped were used by Reeder (1957) to compute total pumpage in the lower Animas Valley during 1948, 1949, 1950, and 1951. Prior to 1951, internal combustion engines were used to power most of the pumps used for irrigation. In 1951 and 1952, electric power was introduced into the valley and many internal combustion engines were replaced by electric motors. In 1952, the State Engineer began to estimate total pumpage in the valley on the basis of electric power records and pump ratings. It is likely that a number of irrigation pumps were operated by internal combustion engines after 1952 and it appears that this pumpage has been neglected in the State Engineer's estimates. The purpose of this discussion is to indicate that the estimates of pumpage over the entire valley may be subject to considerable error and contribute to errors in the transient calibration. Figure 8-11 shows the State Engineer's estimates for total irrigation pumpage in the lower Animas Valley from 1948 through 1958.

Figure 8-11. Annual irrigation pumpage. The plotted data are taken from Reeder (1957, 1960, 1961, 1962).

To apportion these pumpage values over the simulation grid, it was necessary to assign a particular pumping rate to various grid blocks in each year. For the 1948 pumping season, Reeder (1957) lists total pumpage for 24 selected wells and their locations. The total estimated pumpage for these 24 wells was 5375 acre-ft, whereas, the total pumpage for the entire valley was 6400 acre-ft. The 24 wells listed by Reeder (1957) were located on the grid and their total pumpage was assigned to the grid block in which they were located. The remaining 1025 acre-ft was assumed pumped by other wells in the blocks occupied by the 24 wells for which locations were given and apportioned among these blocks. For example, if a block contained 15% of the 5375 acre-ft pumped, 15% of the 1025 acre-ft was added to that amount. This approach is reasonable because of the fact that the 24 wells listed were fairly representative of the centers of pumpage for the valley.

Reeder (1957, Figures 23 and 24) gives the irrigated acreage in 1950 and 1955. These maps, the result of surveys performed by the State Engineer's Office, were superimposed over the simulation grid and pumpage was assigned to blocks according to the percentage of total-irrigation land found in that block. The 1950 map (Reeder 1957) was used to determine the spatial distribution of pumpage for 1949, 1950, and 1951. The 1955 map (Reeder 1957) was used to assign pumpage for 1952, 1953, and 1954.

Since drawdown in a pumped aquifer is directly proportional to pumping rate, errors in estimates of total pumpage and distribution of pumpage could have a significant effect on the computer model. The relative importance of such errors, as compared with errors in other parameters, is discussed in the section on sensitivity analysis.

The durations of pumping periods were determined from data in Reeder (1957). Values for total pumpage and duration of the pumping season are

summarized in Table 8-1 for both the transient calibration and the verification period. Also included in Table 8-1 are data on total irrigated acreage and average application per acre.

One assumption made in setting up the transient model was that none of the pumped groundwater percolated back down to the aquifer after irrigation application. This assumption may be reasonable in light of the high potential for evapotranspiration and the data on water availability for crop use (i.e., average groundwater application plus growing season precipitation) for the period 1948 through 1958 (see Figure 8-12). Consumptive use values for alfalfa, cotton, and sorghum, the three most common crops in the Animas Valley, are also included in Figure 8-12. These data imply that there is little irrigation water available for recharging the aquifer. However, if some recharge from irrigation does occur, which is probably necessary for leaching salts, then this amount would appear lumped along with pumping in the source-sink term. That is, in some nodes, in order to calibrate the model properly, the net withdrawal was less than the pumping rate by an amount which may be due to recharge. However, when averaged over all nodes in the mesh, net withdrawals equaled net pumping.

The alluvial aquifer system in the lower Animas Valley is a rather heterogeneous mixture of layers of clay, sand, and gravel material. According to Reeder (1957), the groundwater is locally under artesian pressure but overall it may be characterized as a water-table aquifer. For the purposes of the computer simulation, the aquifer was assumed to be confined. This assumption is valid where water-level drawdowns are less than about 10% of the total aquifer thickness. Maximum drawdown during the calibration period was about 30 ft (Reeder 1957), and the aquifer is perhaps 300 to 1500 ft thick.

Table 8-1. Irrigation data in the Animas Valley.

Year	Total Pumpage (acre-ft)	Duration of Pumping Season (days)	Total Irrigated Acreage (acres)	Average Application (acre-ft/acre)
1948	6,400 ¹	150 ¹	4,000 ¹	1.6
1949	11,000 ¹	180 ¹	6,800 ¹	1.6
1950	15,000 ¹	195 ¹	7,900 ¹	1.9
1951	18,000 ¹	195 ¹	9,000 ¹	2.0
1952	21,000 ¹	195 ¹	10,900 ¹	1.9
1953	24,000 ¹	220 ¹	11,000 ¹	2.2
1954	19,500 ¹	220 ¹	11,400 ¹	1.7
1955	19,800 ¹	195 ¹	11,400 ¹	1.7
1956	22,700 ²	195 ⁵	12,500 ³	1.8
1957	19,500 ³	195 ⁵	12,800 ³	1.5
1958	16,600 ⁴	195 ⁵	12,800 ⁴	1.3

Sources: (1) Reeder (1957); (2) Reeder (1960); (3) Reeder (1961);
(4) Reeder (1962); and (5) estimated data.

Figure 8-12. Total water availability and consumptive use in the Animas Valley for the period 1948 through 1958 (Blaney and Hanson 1965).

In order to perform the transient simulation, it was necessary to input an initial estimate of the storage coefficient. Reeder (1957) calculated an average value of storage by dividing the volume of water pumped from the entire valley by the volume of dewatered sediments calculated from water-level change maps. Values of the storage coefficient computed in this manner range from 0.07 to 0.14.

Summers (1967) performed a Theis solution analysis of data from 1948 through 1966 in wells located four or more miles from the center of pumpage as computed by Reeder (1957) for 1955 data. This analysis (Summers 1967) yielded values for the storage coefficient of 0.056-0.071. Initially, a storage coefficient of 0.11 was assigned to all nodes in the numerical model.

The first run with transmissivity values entered for the steady-state model calibration and a storage coefficient equal to 0.11 at all nodes produced surprisingly good agreement between computed and observed water levels. Only minor adjustments in the storage coefficients were necessary during the calibration period. Since distribution of pumpage was also a variable to a certain extent, pumpage at various nodes was adjusted slightly, but the overall estimated pumpage was maintained for all pumping periods. Transmissivity was also adjusted slightly at a few nodes. Figure 8-13 shows contours of computed drawdowns at the end of the model calibration and contours of observed drawdowns as measured in January 1955 (Reeder 1957). Figures 8-14 and 8-15 show the distribution of transmissivity and storage coefficient values, respectively, as determined in the calibration procedure.

Model Verification

The model was calibrated over a relatively long period of time, spanning seven irrigation seasons (i.e., April 1948 to January 1955). Although it

Figure 8-13. Measured (Reeder 1957) and simulated drawdown (in ft) for January 1955.

Figure 8-14. Distribution of transmissivity values after completion of the model calibration procedure.

Figure 8-15. Distribution of storage coefficient values after completion of the model calibration procedure.

would be desirable to verify the model with the calibrated transmissivity and storage coefficients for a period time equal to or longer than the calibration period, only four years of reliable pumping data are available. After the State Engineer extended the declared basin in February 1956 to include an additional 221 square miles to the east and south of the original declared basin, rather extensive irrigation pumpage started to the southeast of the original declared basin in Summer 1959 (Putnam, personal communication 1981). Therefore, pumpage figures in the State Engineer's Reports subsequent to 1958 include the development southeast of the modeled area. In addition, the percentage of pumping occurring in the extended portion of the basin after 1958 is not known. Thus, it is not possible to assign pumping rates to the nodes of the model with any certainty.

The verification period encompassed four irrigation seasons, from January 1955 to January 1959. Values of total pumpage are shown in Table 8-1. The duration of pumpage was assumed to be from April 1 to September 30 of each year. The distribution of pumpage was assigned in the same manner as for the model calibration using the 1955 irrigated acreage map of Reeder (1957, Figure 24).

Figure 8-16 is a plot of computed heads versus actual water levels in wells located within the corresponding grid blocks for January 1959 at the end of the verification period. Only three wells which were located at grid corners or boundaries were omitted from this plot. The goodness of fit of these 33 data points to the line defining equality was computed to be $r^2 = 0.95$, which is considered to be an excellent result.

Figures 8-17 through 8-20 show observed and calculated hydrographs of wells in various parts of the valley. The well locations and the locations of the corresponding prediction nodes are shown in Figure 8-21. These wells were

Figure 8-16. Observed and simulated water-level elevations for January 1959. The observed data are taken from Reeder (1962).

Figure 8-17. Observed (o) and simulated (Δ) water-level elevations at Well 24.20.22.222. The observed data are taken from Reeder (1957, 1960, 1961, 1962).

Figure 8-18. Observed (o) and simulated (Δ) water-level elevations at Well 25.19.7.234. The observed data are taken from Reeder (1957, 1960, 1961, 1962).

Figure 8-19. Observed (o) and simulated (Δ) water-level elevations at Well 16.10.16.422. The observed data are taken from Reeder (1957, 1960, 1961, 1962).

Figure 8-20. Observed (o) and simulated (Δ) water-level elevations at Well 27.19.19.433. The observed data are taken from Reeder (1957, 1960, 1961, 1962).

Figure 8-21. Location of wells and nodes in Figures 8-17 through 8-20 and corresponding grid blocks in the finite-difference mesh.

chosen to represent all the areas of the valley, except the pumping center near Cotton City. Note that Figure 8-18 is the hydrograph of Well 25.19.7.234 in the localized geothermal area. Figures 8-22, 8-23, and 8-24 illustrate cross-sections of the water table at the beginning of the simulation (April 1948), the end of calibration (January 1955), and the end of verification (January 1959), respectively.

The predicted heads for wells 25.19.7.234 and 27.19.19.433 appear to be converging on the actual-head values, while the predicted heads for wells 24.20.22.222 and 26.20.26.422 appear to be diverging from the observed heads. These trends are not particularly sharp and may be due to a poor estimate of the pumpage distribution over time. It is not evident that any of these trends is coincident with the end of the calibration period. The model appears to underestimate drawdowns somewhat across the center of pumping, although the shape of the predicted water table conforms well to the shape of the real water table (see Figure 8-24). In general, the model predictions agree rather well with the observed water-table response, considering the uncertainty associated with the input parameters.

Although the model verification process suggests that the selected aquifer characteristics and boundary conditions are representative of the real conditions, because of the large number of unknowns in this analysis, there may be other combinations of parameters which give as good or better results. However, the selected model parameters are considered well within reasonable limits based on hydrogeologic evidence.

Sensitivity Analysis

Due to the inherent uncertainty in the calibrated model, it is important to understand how sensitive the model results are to changes in the various

Figure 8-22. Observed (o) and simulated (Δ) water-level elevations in an east-west cross-section through the irrigation pumping center in April 1948. The observed data are taken from Reeder (1957).

Figure 8-23. Observed (o) and simulated (Δ) water-level elevations in an east-west cross-section through the irrigation pumping center in January 1955. The observed data are taken from Reeder (1957).

Figure 8-24. Observed (o) and simulated (Δ) water-level elevations in an east-west cross-section through the irrigation pumping center in January 1959. The observed data are taken from Reeder (1962).

input parameters. In order to perform a sensitivity analysis, a pumping and a non-pumping node were selected and the model parameters were adjusted at these nodes. First, a run was made with the initial parameter values for comparison to the runs in which parameters were changed by a known amount. A separate computer run was made for each parameter which was perturbed. The changes in water level induced by adjusting a particular parameter was monitored both locally in grid blocks adjacent to the perturbed block and over the entire grid. For the purposes of the sensitivity analysis, each computer run involved a period of no irrigation pumping followed by a period of irrigation pumping, which was followed, in turn, by a period of no irrigation pumpage. This sensitivity test procedure encompassed 27 time steps.

Pumping rate, transmissivity, and storage coefficient values were each perturbed by $\pm 50\%$ at the chosen pumping node (i.e., node 6-20 in Figure 8-9). The initial head was perturbed by 10% with respect to a 4000 ft above mean sea-level datum so that the absolute change in head was 16.4 ft. Figure 8-25 shows the relative effects induced by these perturbations at the end of the last time step. The cumulative error, as plotted, was defined as the absolute value of the error at each node summed over the entire grid.

The same procedure was followed at the non-pumping node (i.e., node 6-26 in Figure 8-9), except that the absolute change in initial head was 13.2 ft. The effects of these perturbations are shown in Figure 8-26.

Figures 8-25 and 8-26 indicate that the model appears to be most sensitive to errors in initial head and least sensitive to errors in storage coefficient. Straight lines were drawn from the origin to the data point in each test for convenience; however, it is not expected that the head-change relationship indicated for transmissivity and storage would be strictly linear. For the pumping node, a 50% increase in transmissivity caused a

Figure 8-25. Model sensitivity test for hydraulic head, pumping rate (Q), transmissivity (T), and storage coefficient (S) at pumping node 6-20.

Figure 8-26. Model sensitivity test for hydraulic head, transmissivity (T), and storage coefficient (S) at non-pumping node 6-26.

larger change in head than a 50% increase in pumping. However, the reverse was true when transmissivity and pumping were decreased by 50%. This result was expected based on similar tests with analytical solutions for flow to a single well. Although errors due to a 50% change in pumpage and transmissivity are of the same order of magnitude when the absolute error values are summed over the entire grid, it is likely that errors in the distribution of pumpage values are in general less than 10%, whereas, errors in the distribution of transmissivity values are somewhat larger.

The transient behavior of hydraulic head changes due to the parameter perturbation are shown at node 6-20 as a function of time (see Figure 8-27). The left axis is the cumulative error throughout the computer grid, while the right axis is the ratio of the local error to the cumulative error. The local error is defined as the absolute value of the head change in the block where the perturbation was induced plus the sum of the head changes in the eight surrounding blocks. The ratio of local error to cumulative error is a measure of the speed with which the head change propagates over the grid.

Figure 8-27 shows that the cumulative change in computed head due to a change in initial head is maintained at an almost constant level throughout the simulation period. This error is spread out over the grid with time and it does not appear to be affected by the period of pumping.

Figure 8-28 illustrates the transient behavior of the error produced by a transmissivity perturbation. Note that the cumulative error increases with time as the ratio of local error to cumulative error decreases. Neither the ratio nor the cumulative error behavior appears to be affected by irrigation pumping.

The effects of an error in pumping rate with time are shown in Figure 8-29. As expected, there is no increase in cumulative error during

Figure 8-27. Errors in computed head due to an increase in initial water level of 16.4 feet at node 6-20.

Figure 8-28. Errors in computed head due to a 50 percent increase in transmissivity at node 6-20.

Figure 8-29. Errors in computed head due to a 50 percent increase in pumping rate at node 6-20.

non-pumping periods. The cumulative error increases linearly with time during the irrigation pumping period. The cumulative error does not decrease during the final non-pumping period, although the head change is propagating away from the perturbed node at all times. After a long period of time, the cumulative error would decrease to zero, as recharge would gradually replace the volume withdrawn from storage during pumping.

Figure 8-30 shows the effect of a storage coefficient perturbation at node 6-20. No error is produced during the non-pumping period. This result is expected because of the existence of steady-state conditions prior to pumping. Cumulative error increases slowly during the pumping period but then decreases somewhat during the subsequent non-pumping period. The decrease in error occurs as the system again approaches a steady state following pumping. The storage coefficient affects the rate of spread of the core of depression and has no effect on the steady-state flow field. Because of the reduction of cumulative error during non-pumping periods, errors in the storage coefficient are much less significant than errors in transmissivity or pumping rate.

Hydrologic Data Collection

One objective of this project was to update and expand the data base for groundwater chemistry, temperature, and water-level elevations. Three sampling trips were made to the Animas Valley during the periods of August 6 to 7, 1980, January 5 to 7, 1981, and March 28 to 30, 1981. During the first trip, 15 samples were obtained, many of which were from pumping wells because the month of August occurs near the end of the irrigation season. Eighteen samples were taken in January and 23 were collected in March. During January and March there is little irrigation, so many of the wells sampled in August were not sampled on these two trips.

Figure 8-30. Errors in computed head due to a 50 percent increase in storage coefficient at node 6-20.

At each well, three samples were collected in 500 milliliter plastic bottles which were previously rinsed with the sampled water. One sample was acidified with 3 milliliters of 0.1 normal nitric acid for silica determinations. The water analyses were performed under the direction of Lynn Brandvold, New Mexico Bureau of Mines and Mineral Resources, and are reported in Table 8-2. Temperatures shown in Table 8-2 were measured in the field by the use of a thermometer placed in a one-liter beaker of the sampled water or by a maximum-recording thermometer lowered down the well bore. In the field, hardness was determined using a Hach kit, pH was measured with a portable Orion analog pH meter, and specific electrical conductivity was determined using Yellow Springs and Orion portable conductivity meters. Where possible, water levels in the sampled wells were measured with a chalked steel tape. All field data, excluding temperature, are summarized in Table 8-3.

Figure 8-31 is a map of groundwater temperatures measured during the field program. Thermal groundwater occurs within about 1000 ft of the area of the hot wells where temperatures ranged from 65 to 94°C. Outside of this area groundwater temperatures ranged from 16 to about 24°C. During the sampling period, temperature changes at a single well ranged from 1' to 3.4°C outside the area of the hot wells to 6°C at the hot wells; however, there was no clear trend identified for temperatures increasing or decreasing between the pumping and non-pumping season. This observation may be due to a very small data base, sampling and measurement errors, well construction, and well location with respect to the geothermal fluids. A comparison of the groundwater temperature map published by Summers (1976) and Figure 8-31 indicates that there has been no readily discernable change in groundwater temperature since the 1960's.

Table 8-2. Chemical analyses (in ppm) of water from wells in the Animas Valley, Hidalgo County, New Mexico. The analyses were performed by the New Mexico Bureau of Mines and Mineral Resources.

Well Number	Collection Date	Silica (SiO ₂)	Sodium (Na)	Potassium (K)	Magnesium (Mg)	Calcium (Ca)	Carbonate (CO ₃)	Bicarbonate (HCO ₃)	Chloride (Cl)	Sulfate (SO ₄)	Nitrate (NO ₃)	Lithium (Li)	Total Dissolved Solids*ppm	Electrical Conductivity (μmhos/cm @ 25°C)	Temperature (°C)	pH
23.20.36.444 ¹	1/5/81	55.0	350.0	14.8	24.5	75.0	0	152.5	386.0	376.0	0.52	<0.1	1,304	2,010	---	8.1
24.19.20.421 ²	8/6/81	38.0	110.0	2.2	2.8	20.1	13.9	214.0	24.6	55.0	---	<0.1	366	680 ^F	24	8.2
24.20. 1.422 ³	1/5/81	72.0	295.0	12.6	17.0	64.0	0	137.2	244.0	451.0	0.21	<0.1	1,152	1,650	---	7.9
24.20.12.242 ⁴	1/6/81	72.0	114.0	3.0	1.96	12.0	0	167.8	12.0	129.0	1.01	<0.1	357	489	19	8.3
24.20.22.424 ⁵	3/30/81	84.0	59.0	7.0	3.0	35.0	0	137.0	10.0	80.0	1.6	<0.1	348	390	---	6.9
24.20.25.143 ⁶	8/6/80	99.0	250.0	40.0	8.3	122.0	0	276.0	99.0	583.0	---	0.29	1,345	1,875 ^F	20	7.8
24.20.25.424 ⁷	8/7/80	103.0	368.0	32.8	3.6	75.0	0	237.0	160.0	656.0	---	0.62	1,526	2,000	21.5	7.7
24.20.25.424 ⁸	3/28/81	128.0	495.0	25.0	7.3	125.0	0	198.0	206.0	957.0	3.25	0.82	2,046	2,650	20	6.8
24.20.26.212 ⁹	8/6/80	64.0	56.0	2.8	3.0	30.1	0	181.0	12.0	56.0	---	<0.1	316	435 ^F	22	8.2
24.20.34.444 ¹⁰	8/6/80	56.0	60.0	2.9	0.62	39.2	0	220.0	15.0	55.0	---	<0.1	345	450 ^F	19.6	7.9
24.20.34.444 ¹¹	1/6/81	63.0	64.0	2.1	4.0	39.0	0	122.0	14.0	122.0	1.06	---	307	424	17	8.1
24.20.34.444 ¹²	3/28/81	78.0	65.0	2.6	3.7	40.0	0	153.0	16.0	98.0	1.36	<0.1	381	430	18	6.95
24.20.35.212 ¹³	3/28/81	68.0	54.0	2.1	1.9	30.0	0	137.0	10.0	64.0	1.44	<0.1	299	311	20	6.9
24.20.35.221 ¹⁴	8/6/80	46.0	48.0	2.7	2.0	21.0	0	158.0	7.0	40.0	---	<0.1	200	325 ^F	20	7.9
25.19. 7.213 ¹⁵	8/6/80	150.0	305.0	30.0	<0.1	16.1	8.3	68.0	89.0	508.0	---	0.54	982	3,930	88.9	8.5
25.19. 7.234 ¹⁶	3/27/81	163.0	300.0	31.0	0.33	23.0	0	107.0	82.0	513.0	1.03	0.65	1,167	1,500	84	7.3
25.19. 7.234a ¹⁷	1/6/81	140.0	307.5	30.0	0.06	25.0	0	91.5	88.0	536.0	1.32	0.5	1,034	1,510	---	8.0
25.19. 7.234b ¹⁸	8/7/80	216.0	4200.0	1340.0	<0.1	146.0	139.0	68.0	1581.0	8730.0	---	9.5	16,281	18,800	89.4	10.9
25.19. 7.234b	1/6/81	190.0	4428.0	1129.0	0.34	160.0	0	355.0	1690.0	7973.0	46.4	20.0	15,604	20,100	94	8.1
25.19. 7.234c ²⁰	8/7/80	194.0	460.0	40.0	<0.1	62.3	27.8	96.0	123.0	881.0	---	0.92	1,628	2,100	71	8.7
25.19. 7.234c	1/6/81	230.0	420.0	42.0	0.125	52.0	0	122.0	106.0	768.0	2.15	0.6	1,452	2,020	65	8.5
25.19. 7.424 ²²	8/7/80	17.0	90.0	3.6	5.0	31.2	0	254.0	15.0	80.0	---	<0.1	352	600	24.5	7.3
25.19. 7.424 ²³	1/6/81	26.0	100.0	3.6	6.05	34.0	0	167.8	12.0	178.0	0.08	<0.1	418	499	24	7.6
25.19.11.112 ²⁴	3/29/81	43.0	81.0	2.7	23.0	110.0	0	229.0	36.0	283.0	8.8	<0.1	703	1,000	21	6.75
25.19.13.343 ²⁵	3/29/81	43.0	59.0	2.6	24.0	99.0	0	259.0	16.0	230.0	1.15	<0.1	561	800	18	6.6
25.20. 1.242 ²⁶	8/7/80	100.0	342.0	28.5	9.8	96.5	5.6	237.0	121.0	692.0	---	0.56	1,514	1,600	24.1	8.0

Table 8-2. (continued).

Well Number	Collection Date	Silica (SiO ₂)	Sodium (Na)	Potassium (K)	Magnesium (Mg)	Calcium (Ca)	Carbonate (CO ₃)	Bicarbonate (HCO ₃)	Chloride (Cl)	Sulfate (SO ₄)	Nitrate (NO ₃)	Lithium (Li)	Total Dissolved Solids* (ppm)	Electrical Conductivity (umhos/cm @ 25°C)	Temperature (°C)	pH
25.20. 8.111 ²⁷	1/ 6/81	43.0	77.0	3.4	8.0	42.0	0	152.5	8.0	159.0	0.6	<0.1	375	600	21.5	7.9
25.20.12.114 ²⁸	8/6/80	45.0	105.0	4.0	5.8	62.3	0	214.0	37.0	185.0	---	<0.1	507	680 ^F	21.4	7.8
25.20.12.114 ²⁹	3/28/81	62.0	100.0	3.8	6.8	61.0	0	153.0	32.0	225.0	1.35	<0.1	570	750	18	6.9
25.20.13.214 ³⁰	8/7/80	43.0	174.0	9.0	4.6	116.0	0	120.0	125.0	415.0	---	0.21	910	1,380	20.3	7.4
25.20.13.214a ³¹	8/7/80	34.0	292.0	17.5	49.0	314.0	0	214.0	332.0	1063.0	---	0.36	2,213	2,850	19	7.4
25.20.13.214a ³²	3/28/81	58.0	340.0	27.0	43.0	230.0	0	183.0	266.0	917.0	10.5	0.32	1,984	2,600	20	6.75
25.20.15.413 ³³	1/7/81	55.0	67.0	1.8	2.6	28.0	0	137.0	4.0	103.0	0.96	<0.3	276	370	16	7.9
25.20.15.444 ³⁴	1/7/81	41.0	64.0	1.8	4.0	31.0	0	137.0	6.0	116.0	0.85	<0.1	292	360	---	7.9
25.20.24.313 ³⁵	8/7/80	28.0	97.0	4.5	7.8	83.4	0	186.0	84.0	194.0	---	<0.1	597	950	19.6	7.7
25.20.34.333 ³⁶	1/7/81	46.0	120.0	3.2	9.6	102.0	0	152.5	72.0	339.0	10.25	<0.1	733	1,010	---	8.3
26.19.31.433 ³⁷	3/30/81	36.0	103.0	2.0	0.34	7.0	0	168.0	12.0	81.0	1.0	<0.1	326	415	---	7.5
26.20. 5.442 ³⁸	1/7/81	55.0	110.0	3.6	10.6	95.0	0	152.5	60.0	292.0	8.5	<0.3	656	1,000	---	8.0
26.20. 7.314 ³⁹	1/6/81	40.0	82.0	3.3	6.8	50.0	0	167.8	8.0	190.0	1.96	<0.1	424	620	18	8.1
26.20.14.332 ⁴⁰	3/28/81	55.0	69.0	2.7	4.0	32.	0	122.0	24.0	92.0	5.6	<0.1	345	430	---	7.05
26.20.14.334 ⁴¹	3/28/81	43.0	53.0	2.1	3.95	28.0	0	122.0	16.0	71.0	3.45	<0.1	281	330	23	7.0
26.20.23.244 ⁴²	3/28/81	43.0	59.0	2.5	3.5	26.0	0	137.0	14.0	70.0	2.7	<0.1	289	330	20	6.9
26.20.23.434 ⁴³	3/28/81	55.0	51.0	2.1	5.0	32.0	0	122.0	14.0	81.0	3.25	<0.1	305	340	---	6.95
26.20.24.333 ⁴⁴	1/6/81	30.0	57.0	2.3	5.5	24.0	0	137.0	14.0	63.0	2.38	<0.1	237	380	---	8.3
26.20.24.333a ⁴⁵	3/28/81	52.0	54.0	2.4	4.25	24.0	0	153.0	14.0	57.0	3.15	<0.1	287	340	---	6.95
26.20.35.111 ⁴⁶	1/7/81	43.0	73.0	1.7	1.18	21.0	0	137.0	6.0	101.0	0.85	<0.3	273	370	16	8.4
26.20.36.242 ⁴⁷	3/30/81	50.0	69.0	3.0	1.82	16.0	0	153.0	8.0	60.0	2.25	<0.1	286	329	---	7.8
26.21.12.114 ⁴⁸	1/6/81	40.0	77.0	3.2	6.55	43.0	0	152.5	6.0	149.0	0.43	<0.1	362	600	---	7.8
26.21.13.322 ⁴⁹	1/6/81	46.0	82.0	3.3	6.65	49.0	0	152.5	6.0	158.0	0.35	<0.1	382	600	23	8.4
27.19.19.421 ⁵⁰	3/29/81	40.0	43.0	2.3	7.25	36.0	0	122.0	16.0	74.0	3.9	<0.1	284	365	20.5	7.0
27.19.20.323 ⁵¹	3/29/81	45.0	40.0	2.1	6.5	26.0	0	107.0	14.0	53.0	3.6	<0.1	243	300	23.0	6.6
27.20.12.24 ⁵²	3/30/81	43.0	78.0	4.2	15.0	127.0	0	107.0	54.0	338.0	5.75	<0.1	719	1,000	---	6.7
27.20.16.444 ⁵³	3/30/81	40.0	72.0	2.4	4.0	30.0	0	137.0	10.0	164.0	0.84	---	391	440	---	7.15
27.20.21.133 ⁵⁴	3/30/81	33.0	60.0	3.1	12.0	38.0	0	153.0	14.0	120.0	2.95	<0.1	435	450	---	6.9
28.19.10.334 ⁵⁵	3/29/81	50.0	13.0	2.7	14.7	40.0	0	122.0	16.0	57.0	5.15	<0.1	260	330	---	6.95
28.19.20.24 ⁵⁶	3/29/81	50.0	61.0	2.0	0.93	28.0	0	137.0	10.0	73.4	1.10	<0.1	295	410	21	6.95

* Concentration of total dissolved solids was determined by adding half the bicarbonate concentration (HCO₃) to the concentrations of the other major constituents.

F Field measurement, all other measurements except temperature made in the laboratory.

Table 8-2. (continued)

Footnotes:

1. Domestic well, sampled from spigot in yard, well is reportedly 180 ft deep.
2. Nation Well, pumping windmill, water level is 161 ft below surface.
3. Domestic well, sampled from spigot in yard, well is reportedly 90 ft deep.
4. Electric turbine pump, allowed to pump 5 to 10 minutes before sampling, well is reportedly 90 ft deep.
5. Domestic well, sampled from spigot on pressure tank.
6. Domestic well, sampled from galvanized discharge pipe (no pressure tank), well was pumped for several hours prior to sampling.
7. 40-hp electric turbine, well is reportedly 150 ft deep, perforated from 117 to 150 ft.
8. Same as 7 above, well was pumped for 5 minutes before sampling.
9. Pumping windmill, reportedly 60 ft deep.
10. Pumping windmill, reportedly 70 ft deep, depth to water was 57.12 ft.
11. Pumping windmill, same as 10 above.
12. Pumping windmill, same as 10 above.
13. Pumping windmill.
14. Domestic well, electric submersible pump, reportedly 100 ft deep, perforated bottom 10 feet.
15. McCant's Hot Well, depth to water 71 ft, sample was bailed from open well with pump pulled, less than 1 well bore volume was removed, therefore sample is questionable.
16. Well at northwest corner of Burgett's greenhouse, electric turbine pump, well pumping when sampled, sample taken from leaky fitting around well head.
17. Sample taken from spigot inside Burgett's greenhouse, pumping well was on south side of greenhouse.
18. Hot well, open hole not equipped with pump, sample was bailed but less than 1 well bore volume was removed, therefore sample is questionable.

19. Same as 18 above, sample questionable.
20. Hot well, open hole, not equipped with pump, sample was bailed but less than 1 well bore volume was removed, therefore sample is questionable.
21. Same as 20 above, sample questionable.
22. Open hole, not equipped with pump, water level is 86.94 ft below surface, sample was bailed but less than 1 well bore volume was removed, therefore sample may be questionable.
23. Same as 22 above, sample questionable.
24. Pumping windmills, sampled at end of 6-ft discharge line, well is reportedly 350 ft deep.
25. Windmill, pumped dry 2 minutes after releasing brake, water level 38.2 ft below surface.
26. 50-hp electric turbine, sample obtained while well was pumping for irrigation purposes.
27. Domestic well, sampled at end of 30-ft discharge pipe.
28. Well equipped with submersible pump, water is pumped to McCant's hot wells to cool submersible pump, well was pumping when sampled, sample taken from spigot 4 ft from wellhead.
29. Same as 28 above.
30. 40-hp electric turbine, sample taken at pressure release valve 7 ft from wellhead.
31. Well is equipped with electric turbine and electric submersible pump, sample taken from submersible pump after pumping for several minutes.
32. Same well as 31 above, sample taken from submersible pump after well was pumped for 10 to 15 minutes.
33. Pumping windmill, sample taken from 15-ft discharge pipe.
34. Domestic well, sample taken from spigot off pressure tank.
35. Pumping irrigation well equipped with 30-hp electric turbine pump, sample taken at end of 35 ft discharge pipe.
36. Domestic well, sample taken from spigot in yard, well is reportedly 250 ft deep.
37. Domestic well, sample taken from spigot in yard.
38. Domestic well, sample taken from spigot on pressure tank, well is reportedly 175 ft deep.

39. Domestic well, sample taken from 8-ft long rubber hose discharging water from a submersible pump, no pressure tank.
40. Pumping irrigation well equipped with electric turbine, sample taken from end of 150 ft discharge pipe, bowls are set at 360 ft, northernmost of a row of 5 wells.
41. Pumping irrigation well equipped with 100-hp electric turbine, well is reportedly 280 ft deep with bottom 60 ft perforated.
42. Pumping irrigation well equipped with 50-hp electric turbine, sample taken at end of 8-ft discharge line.
43. Pumping irrigation well equipped with gasoline-powered turbine, sample taken at end of 300-ft discharge line, well is reportedly 400 ft deep.
44. Domestic well, sampled from spigot in yard.
45. Pumping irrigation well equipped with gasoline-powered turbine, sampled at end of 100 to 150-ft discharge line.
46. Washburn Well, pumping windmill, sampled at end of 20-ft discharge pipe.
47. Domestic well, sample taken from spigot on pressure tank.
48. Domestic well, sample taken from spigot on pressure tank.
49. Pumping windmill, sample taken from spigot at wellhead, well was reportedly drilled to 700 ft by Phelps-Dodge Corporation.
50. Pumping irrigation well equipped with 75-hp electric turbine, sampled at end of 4-ft discharge line.
51. Pumping irrigation well equipped with 50-hp electric turbine, sample taken from loose fitting 6 ft from wellhead.
52. Domestic well, sample taken from spigot on pressure tank, well is reportedly 500 ft deep.
53. Domestic well, formerly used as an irrigation well but presently equipped with submersible pump, sample taken from spigot 30 ft from pressure tank.
54. Domestic well, sample taken from kitchen tap with all PVC pipe, well is reportedly 405 ft deep.
55. Domestic well, sample taken from spigot in yard, well is reportedly 370 ft deep.
56. Pumping windmill, sample taken from cracked fitting around wellhead.

Table 8-3. Field measurements of water from wells in the Animas Valley, Hidalgo County, New Mexico.

Well Number	Date	Specific Conductivity (μ mhos/cm adjusted to 25°C)	pH	Alkalinity (grains/gallon)	Water Level (feet below land surface)	Land-Surface Elevation* (feet above m.s.l.)
23.20.36.444	1/05/81	1950	6.1	9	-----	----
24.19.20.421	8/06/80	680	6.8	14	160.17	4268
24.20.01.422	1/05/81	1675	5.4	8	75.00 (reported)	4172
24.20.12.242	1/06/81	460	7.6	11	55.00 (reported)	4164
24.20.22.424	3/30/81	----	---	10	-----	----
24.20.25.143	8/06/80	1875	6.3	13	45.40	4170
24.20.25.424	8/07/80	2210	6.7	11	61.02	4184
24.20.25.424	3/28/81	----	---	10	-----	----
24.20.25.444	8/06/80	1600	---	--	59.30	4182
24.20.26.212	8/06/80	435	6.9	9	-----	----
26.20.34.444	8/06/80	450	6.3	10	56.22	4182
26.20.34.444	8/06/80	450	7.4	9	-----	----
26.20.34.444	1/06/81	----	---	10	-----	----
24.20.35.212	3/28/81	----	---	8	-----	----
24.20.35.221	8/06/80	325	6.5	10	-----	----

Table 8-3. (continued).

Well Number	Date	Specific Conductivity (μ mhos/cm adjusted to 25°C)	pH	Alkalinity (grains/gallon)	Water Level (feet below land surface)	Land-Surface Elevation* (feet above m.s.l.)
25.19. 7.133	8/07/80	-----	---	--	70.98	4193
25.19. 7.234	3/27/81	10,000	7.1	5	69.90	4204
25.19. 7.234a	1/06/81	2000	7.4	5	-----	----
25.19. 7.234b	8/02/80	40,900	---	25	~92.50	4206
25.19. 7.234b	1/06/81	off scale	9.4	interference	~106.20	4206
25.19. 7.234c	8/07/80	-----	---	--	77.30	4207
25.19. 7.234c	1/06/81	2500	8.4	interference	~73.70	4207
25.19. 7.324	8/07/80	-----	---	--	61.30	4197
25.19. 7.424	8/07/80	700	6.4	13	86.94	4226
25.19. 7.424	1/06/81	575	4.8	13	89.10	4226
25.19.11.112	3/29/81	-----	---	17	-----	----
25.19.13.343	3/29/81	-----	---	21	38.20	4971
25.20. 1.242	8/07/80	2250	6.6	13	-----	----
25.20. 8.111	1/06/81	1200	8.1	9	115.00	4218
25.20.12.114	8/06/80	825	6.1	11	-----	----
25.20.12.114	3/28/81	-----	---	10	-----	----

Table 8-3. (continued).

Well Number	Date	Specific Conductivity (μ mhos/cm adjusted to 25°C)	pH	Alkalinity (grains/gallon)	Water Level (feet below land surface)	Land-Surface Elevation* (feet above m.s.l.)
25.20.13.214	8/07/80	1500	6.3	10	-----	----
25.20.13.214a	8/07/80	2650	6.3	13	86.70	4194
25.20.13.214a	3/28/81	1100	---	11	-----	----
25.20.15.413	1/07/81	400	7.4	9	-----	----
25.20.15.444	1/07/81	400	6.8	9	-----	----
25.20.24.313	8/07/80	1050	---	--	-----	----
25.20.34.333	1/07/81	1050	6.3	10	-----	----
26.19.31.433	3/30/81	-----	---	10	-----	----
26.20. 5.442	1/07/81	1050	6.8	11	-----	----
26.20. 7.314	1/06/81	550	7.6	12.5	-----	----
26.20.13.422	3/28/81	-----	---	--	87.00	4336
26.20.14.332	3/28/81	-----	--	7.5	-----	----
26.20.14.334	3/28/81	-----	--	9	-----	----
26.20.23.244	3/28/81	-----	--	9	-----	----
26.20.24.333	1/06/81	375	6.8	8.5	-----	----
26.20.24.333a	3/28/81	-----	7.5	---	-----	----
26.20.35.111	1/07/81	425	8.1	9	-----	----

Table 8-3. (continued).

Well Number	Date	Specific Conductivity (μ mhos/cm adjusted to 25°C)	pH	Alkalinity (grains/gallon)	Water Level (feet below land surface)	Land-Surface Elevation* (feet above m.s.l.)
26.20.36.242	3/30/81	---	---	10.0	-----	----
26.21.12.114	1/06/81	600	8.2	9.5	-----	----
26.21.13.322	1/06/81	675	7.8	10.0	-----	----
27.19.19.421	3/29/81	---	---	8.0	-----	----
27.19.20.323	3/29/81	---	---	8.5	-----	----
27.19.34.141	3/29/81	---	---	----	217.2	4484
27.20.12.24	3/30/81	---	---	6.5	-----	----
27.20.16.444	3/30/81	---	---	10.0	-----	----
27.20.21.133	3/30/81	---	---	9.5	-----	----
28.19.10.334	3/29/81	---	---	7.0	-----	----
28.19.20.24	3/29/81	---	---	9.5	-----	----

*Land surface elevation taken from U. S. Geological Survey 7.5' and 15' quadrangles.

Figure 8-31. Groundwater temperature map (in °C) based on data collected in 1980 and 1981.

Figure 8-32 shows the spatial and temporal distribution of total dissolved solids concentrations of selected wells in the study area. Based on these data, an empirical relationship was developed by linear regression of total dissolved solids concentration in parts per million and electrical conductivity in micromhos per centimeter at 25°C (see Figure 8-33). According to this regression, values in micromhos/cm may be multiplied by 0.74 to obtain total dissolved solids in parts per million.

Maps showing concentrations of chloride, sulfate, sodium, lithium, and silica and the ratio of equivalent weights of calcium and chloride are shown in Figures 8-34 through 8-39, respectively. These maps generally outline a zone of relatively high concentration of constituents in a plume extending roughly from one mile southwest of the hot wells northward to more than eight miles for some concentrations such as chloride, sulfate, and sodium. Lithium appears to be a particularly useful geochemical indicator of the thermal groundwater (see Figure 8-37), as it is above detectable limits (i.e., 0.22 ppm) only near the hot wells. Some of these maps (see Figures 8-32, 8-34, 8-35, and 8-37) also suggest that a zone of relatively high concentration of constituents trends southwest from the hot wells in a manner which appears to be consistent with the trend described by Logsdon (1981). As in the case of groundwater temperatures, a general tendency for concentrations of the selected constituents to either increase or decrease from the pumping to non-pumping period could not be observed. Comparison of another map of sodium concentration (Summers 1976) with Figure 8-36 indicates that sodium concentrations have decreased near the hot wells and increased in the plume area to the north. There is no apparent explanation for this change in sodium concentration.

Figure 8-32. Total dissolved solids concentration map (in ppm) based on data collected in 1980 and 1981.

Figure 8-33. Total dissolved solids versus specific electrical conductivity.

Figure 8-34. Chloride concentration map (in ppm) based on data collected in 1980 and 1981.

Figure 8-35. Sulfate concentration map (in ppm) based on data collected in 1980 and 1981.

Figure 8-36. Sodium concentration map (in ppm) based on data collected in 1980 and 1981.

Figure 8-37. Lithium concentration map (in ppm) based on data collected in 1980 and 1981.

Figure 8-39. Ratio of equivalent weights of calcium to chloride based on data collected in 1980 and 1981.

Groundwater in two wells in the Pyramid Mountain area east of the hot wells appears to have chemical characteristics which are different than groundwater in the valley. Well 25.19.11 is reported to be drilled to a depth of 350 ft in bedrock and Well 25.19.13 is a shallow well located in a narrow canyon (see Table 8-2). Both wells are presumed to be in the groundwater recharge area inferred from the flow net in Figure 8-8. However, concentrations of most ions in these two wells are generally greater than in groundwater in the non-thermal area of the valley. These water-quality data may indicate that this mountain area does not contribute a significant amount of recharge to the main alluvial aquifer.

Conclusions

A two-dimensional groundwater flow model was calibrated by adjusting aquifer properties until there was a reasonable agreement between observed and simulated water levels for the period 1948 to 1955. Application of the kriging technique to specific capacity and pumping test data, in conjunction with other hydrogeologic interpretations, resulted in a minimal number of trial computer runs required for the calibration. The calibrated model was run with irrigation pumping data from 1955 to 1959, and predicted water levels agree rather well with those recorded in the field for that period.

The distribution of transmissivity values from the model calibration indicates that there is a zone of low transmissivity stretching northward across the valley from the area of the Quaternary lava flow toward the hot wells. By comparison, transmissivity values are, in general, almost an order of magnitude higher in the northcentral portion of the valley, northwest of

the hot wells. Changes in transmissivity are probably due mostly to changes in the valley-fill thickness.

The existing water chemistry and temperature data base was updated by sampling selected wells in the valley during August 1980, January 1981, and March 1981. These data generally show a plume of relatively high concentrations down gradient from the area of the hot wells. Groundwater temperatures in the Lightning Dock KGRA do not appear to have changed significantly since the 1960's.

References

- Binsariti, A. A., 1980, Statistical analyses and stochastic modeling of the Cortaro Aquifer in southern Arizona: University of Arizona, Ph.D. dissertation, 243 pp.
- Blaney, H. F., and Hanson, E. G. 1965, Consumptive use and water requirements in New Mexico: New Mexico State Engineer's Office, Technical Report 32, 82 pp.
- Deal, E. G., and Elston, W. E., 1982, Geology of the Lightning Dock Known Geothermal Resource Area and vicinity, Pyramid Mountains and Animas Valley, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 177 [In Press].
- Deal, E. G., Elston, W. E., Erb, E. E., Peterson, S. L., Reiter, D. E., Damon, P. E., and Shafiquallah, M., 1978, Cenozoic volcanic geology of the Basin and Range Province in Hidalgo County, southwestern New Mexico, in Callendar, J. F., Wilt J. C., and Clemons, R. E., eds., Land of Cochise Southern Arizona: New Mexico Geological Society, 29th Field Conference Guidebook, p. 219-229.
- Doty, G. C., 1960, Reconnaissance of groundwater in Playas Valley, Hidalgo County, New Mexico: New Mexico State Engineer's Office, Technical Report 15, 40 pp.
- Elston, W. E., Erb, E. E., and Deal, E. G., 1979, Tertiary geology of Hidalgo County, New Mexico: New Mexico Geology, v. 1, no. 1, p. 1, 3-6.
- Fleischhauer, H. L., Jr., 1977, Quaternary geology of Lake Animas, Hidalgo County, New Mexico: New Mexico Institute of Mining and Technology, M. S. thesis, 149 pp.
- Gabin, V. L., and Lesperance, L. E., 1977, New Mexico climatological data, precipitation, temperature, evaporation, and wind; monthly and annual means: W. K. Summers and Associates, Socorro, New Mexico, 436 pp.
- Hawkins, D. B. 1981, A computer modeling study of the groundwater flow regime in the Lower Animas Valley, Hidalgo County, New Mexico: New Mexico Institute of Mining and Technology, independent study report, 105 pp.
- Kintzinger, P. R., 1956, Geothermal survey of hot ground near Lordsburg, New Mexico: Science, v. 124, p. 629-630.
- Logsdon, M. J., 1981, The aqueous geochemistry of the Lightning Dock Known Geothermal Resource Area, Animas Valley, Hidalgo County, New Mexico: University of New Mexico, M. S. thesis, 239 pp.

- Marvin, R. F., Naeser, C. W., and Mehnert, H. H., 1978, Tabulation of radiometric ages, including unpublished K-Ar and fission-track ages for rocks in southeastern Arizona and southwestern New Mexico, in Callendar, J. F., Wilt, J. C., and Clemons, R. E., eds., Land of Cochise, Southern Arizona: New Mexico Geological Society, 29th Field Conference Guidebook, p. 243-253.
- O'Brien, K. M., and Stone, W. J., 1981, Water-level data compiled for hydrogeologic study of Animas Valley, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 130, 13 pp.
- Putnam, L., 1981, Personal communication, New Mexico State Engineer's District Office, Deming, New Mexico.
- Reeder, H. O., ed., 1957, Groundwater in Animas Valley, Hidalgo County, New Mexico: New Mexico State Engineer's Office, Technical Report 11, 101 pp.
- Reeder, H. O., ed., 1960, Groundwater levels in New Mexico, 1956: New Mexico State Engineer's Office, Technical Report 19, 251 pp.
- Reeder, H. O., ed., 1961, Groundwater levels in New Mexico, 1957: New Mexico State Engineer's Office Technical Report 22, 306 pp.
- Reeder, H. O., ed., 1962, Groundwater levels in New Mexico, 1959: New Mexico State Engineer's Office Technical Report 24, 125 pp.
- Schwennesen, A. T., 1918, Groundwater in the Animas, Playas, and San Luis basins, New Mexico: U. S. Geology Survey, Water Supply Paper 422, 152 pp.
- Smith, C., 1978, Geophysics, geology and geothermal leasing status of the Lightning Dock KGRA, Animas Valley, New Mexico, in Callendar, J. F., Wilt, J. C., and Clemons, R. E., eds., Land of Cochise, Southern Arizona: New Mexico Geological Society, 29th Field Conference Guidebook, p. 343-348.
- Strangway, D. W., and Holmer, R. C., 1966, The search for ore deposits using thermal radiation: Geophysics, v. 31, p. 225-242.
- Summers, W. K., 1967, A comparison of long-term and short-term pumping tests: Groundwater, v. 5, no. 3, p. 33-34.
- Summers, W. K., 1976, Catalog of thermal waters in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Hydrologic Report 4, 80 pp.
- Trescott, P. C., Pinder, G. F., and Larson, S. P., 1976, Finite-difference model for aquifer simulation with results of numerical experiments, in Techniques of water-resources investigations of the U. S. Geological Survey: U. S. Geological Survey, Book 7, 116 pp.
- White, D. E., and Williams, D. L., eds., 1975, Assessment of geothermal resources of the U. S.: U. S. Geological Survey, Circular 726, 155 pp.

Wilson, L. G., DeCook, K. J., and Neuman, S. P., 1980, Regional recharge for southwest alluvial basins: U. S. Geological Survey, Contract 14-08-0001-18257.

Yakowitz, S., and Duckstein, L., 1980, Instability in aquifer identification, theory and case studies: Water Resources Research, v. 16, n. 6, p. 1045-1064.

Appendix A

Figure 8A-1. New Mexico well numbering system.