EVALUATION OF GEOTHERMAL POTENTIAL OF
RIO GRANDE RIFT AND BASIN AND RANGE PROVINCE, NEW MEXICO

Final Technical Report
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ABSTRACT

A study was made of the geological, geochemical and geophysical characteristics of potential geothermal areas in the Rio Grande rift and Basin and Range province of New Mexico. Both regional and site-specific information is presented. Data was collected by: 1) reconnaissance and detailed geologic mapping, emphasizing Neogene stratigraphy and structure; 2) petrologic studies of Neogene igneous rocks; 3) radiometric age-dating; 4) geochemical surveying, including regional and site-specific water chemistry, stable isotopic analyses of thermal waters, whole-rock and mineral isotopic studies, and whole-rock chemical analyses; and 5) detailed geophysical surveys, using electrical, gravity and magnetic techniques, with electrical resistivity playing a major role.

Regional geochemical water studies were conducted for the whole State. Integrated site-specific studies included the Animas Valley, Las Cruces area (Radium Springs and Las Alturas Estates), Truth or Consequences region, the Albuquerque basin, the San Ysidro area, and the Abiquiu-Ojo Caliente region. The Animas Valley and Las Cruces areas have the most significant geothermal potential of the areas studied. The Truth or Consequences and Albuquerque areas need further study. The San Ysidro and Abiquiu-Ojo Caliente regions have less significant geothermal potential.

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A NOTE ON THE PUBLICATION OF THIS REPORT

Included in the following Introduction is a description of six appendices amounting to some 2,000 pages of microfiche and another 50 pages of text. The appendices have not been included since all but two documents are now part of the literature available through the references listed in Section 5.

The documents not listed are "Geology of Lightning Dock KGRA and Vicinity" by Deal and Elston, 1978; and the Geochemical Data by Logsdon, 1981. Both of these documents are now available in a single source which is referenced as follows:

Elston, W. E., Deal, E. G. and Logsdon, M. J., 1983, Geology and geothermal waters of Lightning Dock region, Animas Valley and Pyramid Mountains, Hidalgo County, New Mexico: New Mexico Bur. Mines and Min. Res. Circ. 177, 44 p.

1. INTRODUCTION

This report is the result of an integrated study by eight principal investigators of the geological, geochemical and geophysical characteristics of potential geothermal areas in the Rio Grande rift and Basin and Range province of New Mexico, where most of the known thermal anomalies of the state are concentrated (Figure 1). All of these areas have the general characteristics of regions of geothermal energy potential, including young extensional tectonics and volcanism, significant seismicity, high heat flow, young hydrothermal mineral deposits, and numerous hot springs and wells.

The study presents both regional and site-specific information about the geothermal potential of New Mexico. The data was collected by: 1) reconnaissance and detailed geologic mapping, emphasizing Neogene stratigraphy and structure; 2) petrologic studies of Neogene igneous rocks; 3) radiometric age-dating; 4) geochemical surveying, including regional and site-specific water chemistry, stable-isotopic analyses of thermal waters, whole-rock and mineral isotopic studies, and whole-rock chemical analyses; and 5) detailed geophysical surveys, using electrical, gravity and magnetic techniques, with electrical resistivity playing a major role.

Regional geologic and geophysical studies focused on the Rio Grande rift and the Basin and Range province of southwestern New Mexico; regional geochemical water studies were conducted for the whole State. Integrated site-specific studies included the Animas Valley, Las Cruces area (Radium Springs and Las Alturas Estates), Truth or Consequences region, the Albuquerque basin, the San Ysidro area, and the Abiquiu-Ojo Caliente region.

Figure 1. Thermal springs and wells in New Mexico (after Summers, 1965a). Major geothermal targets are circled; underlined areas are discussed in this report: 1 = Ojo Caliente-Abiquiu; 2 = San Ysidro; 3 = Albuquerque-Belen; 4 = Socorro; 5 = Truth or Consequences-Engle; 6 = Radium Springs; 7 = Alum Mountain; 8 = Lightning Dock; 9 = Mangas Trench; 10 = Kilbourne Hole; and 11 = Mesilla Valley (Las Alturas Estates). Jemez Mountains (J) not included.

This report covers the results of three years of field studies, analytical work, laboratory research, and development of research equipment and facilities. About one-half (51%) of the funding was provided by the U.S. Geological Survey for the period June 27, 1975 to June 27, 1977 on grants 14-08-0001-G-255 and 14-08-0001-G-348, the rest by the State of New Mexico through grants administered by the New Mexico Energy Research and Development Program (grants 22, 75-117 and 76-264) for the period January 1, 1975 through December 31, 1977.

Research pertaining to this project has produced extensive published and unpublished work. Published studies by the principal investigators and their students during this project are listed in Appendix 1. This project funded 15 M.S. and Ph.D. theses which were completed during or after the grant period (Appendix 2), with one additional M.S. thesis still outstanding. Microfiche copies of all theses are attached to this report, including a draft of the remaining thesis. In aggregate, thesis work amounted to over 1900 pages of new data and 10 new maps (Table 1). Ten theses are mainly geological, three are geophysical, two geochemical and one is an electrical engineering thesis. In addition, post-doctoral research by E.G. Deal is also included in this project (Appendix 3).

Of additional importance are the many later studies which have their origins in this project, the numerous public and private contacts regarding geothermal energy in New Mexico that this project generated (Appendix 4), and the analytical facilities constructed (Appendix 5). Because this project was designed to gather fundamental data about the geothermal potential of New Mexico and to serve as a foundation for future work, the evidence of the growth of interest in geothermal energy in New Mexico during this project also is considered significant.*

*See p. xix: A note on the publication of this report.

Table 1

M.S. and Ph.D. theses completed under this project (M.S. unless noted).

Author	Advisor	Pages	Map	Comments
Aubele	Kudo	136	Yes	Geology - Volcanology
Broomfield	Callender	75	Yes	Geology - Structure & Igneous Petrology
Dorn	Jiracek	133	No	Geophysics - Electrical
Gerety	Jiracek	86	No	Geophysics - Electrical
Kasten	Kudo	79	Yes	Geology - Volcanology
Lawrence	Woodward	131	Yes	Geology - Structure
Loeber*	Kudo	119	Yes	Geology and Geophysics
Logsdon	Callender	239	No	Geochemistry
May	Woodward	204	Yes	Ph.D.; Geology
Northrop	Landis	60	No	Geochemistry
Olson	Jiracek	154	No	Electrical Engineering
Smith	Jiracek	113	No	Geophysics
Warren	Kudo	156	Yes	Geology - Volcanology
Wilson	Callender	90	Yes	Geology
Zilinski	Callender	69	Yes	Geology - Structure
Zimmerman	Kudo	111	Yes	Geology - Volcanology

*
Unfinished

2. SUMMARY

Regional studies of the geothermal potential of New Mexico included: 1) compilation of geologic and tectonic maps of the Rio Grande rift and southwestern New Mexico; 2) K-Ar age determinations of young volcanic rocks; 3) compilation of water geochemistry for the entire state; 4) delineation of at least seven significant hot-water anomalies on the basis of Na-K-Ca geothermometry, including identification of a major regional anomaly in the southern Rio Grande rift; 5) geochemical characterization of two types of geothermal systems in New Mexico, those associated with deep sedimentary basins and those related to Quaternary magmatic activity; 6) $^{87}\text{Sr}/^{86}\text{Sr}$ measurements on young volcanic rocks to define zones of alteration and to establish background strontium values; 7) oxygen stable isotope geochemistry of natural waters throughout New Mexico; and 8) compilation of regional gravity, magnetic, heatflow and electric data for the Rio Grande rift and adjoining areas. This information is presented and discussed in Chapter 3. On the basis of regional analysis, six major target areas were identified: Lightning Dock area, Las Cruces area (Radium Springs and Las Alturas Estates), Truth or Consequences area, Albuquerque basin, San Ysidro-Jemez area, and the Abiquiu-Ojo Caliente region. Alum Mountain in southwestern New Mexico was also studied as an example of a fossil geothermal system (Chapter 4).

The Lightning Dock area includes parts of the Pyramid Mountains and Animas Valley. Geothermal waters are most likely confined to the valley part. The waters of the Lightning Dock KGRA hot wells are mixed waters containing about 25 percent deep geothermal fluid at approximately 250°C . Although no thermal manifestation of the deep geothermal reservoir other than the hot wells is

known, significant indications of structurally-controlled seepage of chemically distinct reservoir water into the shallow aquifer define a linear trend southwest of the hot wells. The deep water moves up and along a major northeast-trending fault or fault system from a reservoir located southwest of the hot wells, mixing with shallow, cold aquifer waters where this northeasterly trending structure intersects the Quaternary Animas fault and ring-fracture zone of the Muir Cauldron. The heat source for the reservoir is probably Quaternary basaltic magma.

The chemistry of the waters of the Animas Valley is produced by a variety of processes, including evaporation and boiling, water rock interactions at high temperature, and mixing of solutions, including low-temperature groundwaters which have been modified by the dissolution of playa evaporites. The volume of the shallow geothermal reservoir is estimated to be at least 0.75 km^3 , with a total heat content of 2.1×10^{17} joules. Higher temperature water in deeper reservoirs to the southwest may also be present; deep drilling and additional geophysical studies will be required to delineate the deep resource.

In the Radium Springs area bipole-dipole surveys have demonstrated that the southern Jornada del Muerto basin is structurally separated from the Mesilla basin by an inferred intrarift horst. This eliminates the Jornada del Muerto as a reservoir for the hot water of Radium Springs. Three electrical soundings located a 180 m-thick conductive zone at a depth of approximately 100 m. Parts of this zone may be saturated with hot saline water. The uniformity of the sounding data indicates that the interpreted aquifer may extend south of Radium Springs. The hot springs at Radium Springs are artesian and may be an isolated surface expression of the fluids contained in the inferred aquifer. The following is advanced as a hypothesis for the accumulation and upward

migration of thermal waters at Radium Springs. Waters may be rising along a late Tertiary fault bounding the intrarift horst and accumulating in a deep anticlinal trap. A possible heat source for the region is a shallow (5 km deep) magmatic intrusion such as has been suggested to explain nearby magnetotelluric data (Hermance and Pedersen, 1977). Such intrusions of late-Tertiary age or a locally upwarped mantle have been proposed by Decker and others (1975) to account for the heat flow and gravity anomalies in the area.

An estimate of the heat content in the Radium Springs thermal reservoir can not be made since our surveys did not define the extent of the aquifer to the south. The geochemical data published by Swanberg (1975) indicates that the Radium Springs KGRA may be a part of a nearly continuous geothermal system extending from San Diego Mountain to the north along the Rio Grande south into Texas and Mexico.

The Las Alturas thermal anomaly is probably caused by deep circulating water rising along a west-dipping normal fault of Pliocene(?) age which forms the western margin of Tortugas Mountain and its buried extension to the south. The anomaly probably extends many kilometers north and south of the study area and may represent part of a major thermal anomaly along the eastern side of the Mesilla Valley.

The volume of the shallow geothermal reservoir at Las Alturas Estates is estimated to be at least 4 km^3 , with a total heat content of at least 3.8×10^{17} joules. Subsequent drilling has shown excellent agreement between the actual reservoir and the proposed geothermal reservoir as determined by electrical surveys.

Surface manifestations of geothermal activity in the Engle basin and Truth or Consequences area indicate a low geothermal potential. However, Na-K-Ca geothermometry, moderate geothermal gradient ($31^\circ\text{C}/\text{km}$, determined by petrology)

and Pleistocene tectonism and volcanism suggest a potentially more significant geothermal anomaly. The sources of heat for hot springs at Truth or Consequences are probably young basalt intrusions at depth. Spring activity and volcanism are mainly fault-controlled. More work, particularly geoelectric studies, is warranted before firm conclusions can be drawn about reservoir size, heat content and the significance of the geothermal resource in this area.

Geologic and petrologic studies suggest the Albuquerque basin has low geothermal potential, although local thermal anomalies may exist near young volcanic centers such as the Albuquerque volcanos, or at the southwestern edge of the basin (Lucero uplift). Additional heat-flow measurements and detailed geophysical studies should be carried out west of Albuquerque to delineate potential low-temperature geothermal reservoirs. Detailed geophysical work in the Albuquerque basin was done to calibrate geoelectric techniques and to explore deep sources of thermal energy. This work suggests the southern end of the basin has greater geothermal potential, which is caused by a crustal magma body less than 20 km below the surface.

Geologic and geochemical studies suggest that the geothermal potential of the San Ysidro area is low. Because of this, no detailed geophysical studies were undertaken in this area. Oxygen isotope analysis indicates that springs on the west side of the Nacimiento Mountains may have sources in reservoirs with temperatures of about 100°C; this may be potentially attractive for local use. The Jemez Mountains, not studied here except at their margin, have been previously recognized (White and Williams, 1975) as a significant source of geothermal energy.

Based on detailed geologic studies, the geothermal potential of the Abiquiu-Ojo Caliente area is low. No detailed geochemical or geophysical

studies were carried out in this area. All manifestations of geothermal activity such as hot and cold springs, spring deposits and volcanic centers, are strongly controlled by Neogene structural features associated with the Rio Grande rift. Most geothermal activity is Pliocene in age. The most significant geothermal potential in this area probably exists near Ojo Caliente, where dilution by cold groundwater is minimal and elevated isotherms in Precambrian basement may be preserved.

3. REGIONAL STUDIES

Geology

MAPS

The initial phases of geologic work were concentrated on the compilation of existing data on potential geothermal areas in New Mexico. A tectonic map of the Rio Grande rift (Woodward, Callender and Zilinski, 1975), later revised to include all of New Mexico and part of Mexico and Colorado (Woodward and others, 1975, 1978; Tweto, 1978) was compiled from all published, unpublished and original work. Regional overlays (Zilinski and others, 1976 a, b, c) of the tectonic map of the Rio Grande rift for seismicity, gravity, aeromagnetics, heatflow and thermal springs, including measured and chemical temperatures, were also prepared and open-filed with the Department of Geology, University of New Mexico. Similar information was compiled for part of southwestern New Mexico, mainly the Mogollon-Datil volcanic field (Elston and Northrop, 1976).

On the basis of this information and studies by Summers (1965a,b,c; 1976), Reiter and others (1975) and Swanberg (1975), specific target areas were delineated which had the major characteristics of geothermal systems, such as young volcanism, young hydrothermal mineral deposits, significant reservoir potential, heat flow, seismic activity, and hot springs or high calculated chemical reservoir temperatures. Based on a number of considerations, mainly time and manpower, two regions with geothermal potential were excluded as target areas, the Mangas Trench-Gila Hot Springs area and the Socorro area. Later geologic work was confined mainly to target areas, with the focus being detailed and reconnaissance mapping, and field checking existing maps.

K-AR AGE DETERMINATIONS

The results of sixteen K-Ar age determinations are shown in Table 2. Additional dates are tabulated in Kudo and others (1977), Deal and others (1978) and Kelley and Kudo (1978). The dates were determined at the Isotope Geology Laboratory at the University of Arizona through a joint University of New Mexico-University of Arizona program in which each institution paid for one half of each age determination.

The dates compiled in Table 2 are useful in assisting in stratigraphic analysis and resolving problems of correlation in areas in which geologic mapping and geophysical investigations were complete or nearly so. The dates shown in Table 2 are mainly from southwestern New Mexico where, under supervision of Dr. W. E. Elston, mapping was somewhat more complete than in other areas. Those in Kudo and others (1977) and Kelley and Kudo (1978) are for the Albuquerque basin.

With the exception of the granodiorite of the Lordsburg Stock (sample H211), from which extracted biotite yields a 56.52 ± 1.2 m.y. old date, all other dates are 37 m.y. old or younger. While preliminary, it is significant that the Lordsburg Stock biotite still retains its Laramide age of formation considering the amount of Tertiary volcanism in the surrounding area. It is not possible at present to state whether or not any other of the K-Ar dates have been lowered by hydrothermal activity or other processes.

Fifteen whole-rock samples from the Truth or Consequences and the Albuquerque basin areas were sent for K-Ar age determinations in 1977; these samples have not yet been dated by the Isotope Geology Laboratory at the University of Arizona.

TABLE 2

K-Ar Age Results

<u>Sample</u>	<u>Rock Type (name)</u>	<u>Location (T, R)</u>	<u>Age (m.y.)</u>
H-200	Park Tuff	SE 1/4 NW 1/4 sec. 24, T. 31 S., R. 19 W.	29.62 $\pm$ 0.62 (sanidine)
H-201	Gillespie Tuff	NW 1/4 SW 1/4 sec. 11, T. 31 S., R. 19 W.	32.88 $\pm$ 0.70 (biotite)
H-203	Double Adobe Latite	Center of NW 1/4 sec. 24, T. 31 S., R. 19 W.	30.69 $\pm$ 0.66 (biotite)
H-204	Walnut Wells Monzonite Porphyry (stock)	NE 1/4 NW 1/4 sec. 8, T. 31 S., R. 18 W.	34.45 $\pm$ 0.75 (biotite)
H-205	Animas Quartz Monzonite Porphyry (stock)	NW 1/4 SW 1/4 sec. 5, T. 30 S., R. 19 W.	34.83 $\pm$ 0.78 (biotite)
H-208	Andesite Porphyry (dike)	NW 1/4 NW 1/4 sec. 11, T. 25 S., R. 19 W.	29.43 $\pm$ 0.73 (whole rock)
H-211	Lordsburg stock granodiorite porphyry	SE 1/4 SW 1/4 sec. 12, T. 22 S., R. 19 W.	56.52 $\pm$ 1.2 (biotite)
H-212	Rhyolite of North Pyramid Peak	Common corner, SW 14 NE 14 - NW 1/4 SE 1/4 sec. 32 T. 23 S., R. 18 W.	$\sim$ 33
H-214	Oak Creek Tuff	NW 1/4 NW 1/4 sec. 35 T. 30 S., R. 18 W.	35.16 $\pm$ 0.77 (biotite) 38.50 $\pm$ 0.60 (sanidine)
W76-26	Tuff No. 6, Rimrock Mountain Group	SE 1/4 NW 1/4 sec. 17, T. 24 S., R. 18 W.	34.22 $\pm$ 0.56 (sanidine)
W76-28	Tuff No. 1, Rimrock Mountain Group	Center sec. 28, T. 24 S., R. 18 W.	In progress
W76-29	Latite of Uhl Well	SE 14 SW 14 NW 1/4 sec. 28, T. 24 S., R. 18 W.	36.64 $\pm$ 0.80 (biotite)
W76-36	Andesite of Holtcamp Canyon	NE 1/4 SW 1/4 NW 1/4 sec. 24, T. 25 S., R. 18 W.	33.10 $\pm$ 0.70 (whole rock)
W76-89	Tuff of Rattler Well	NE 1/4 SW 1/4 sec. 23, T. 25 S., R. 18 W.	In progress

E-1	Tuff of Guadalupe Canyon	NW 1/4 SW 1/4, sec. 27, T. 22 S., R. 32 E. 31°29'06", 109°04'42"	24.26 ± 0.52 (sanidine)
E-3	Rhyolite of Packer's Trail (San Luis Pass)	NE 1/4, SE 1/4, sec. 26, T. 33 S., R. 19 W. 31°24'12", 108°44'09"	23.00 ± 0.49 (whole rock)
E-4	Basalt of San Luis Pass	SE 1/4 NW 1/4, sec. 35, T. 33 S., R. 19 W. 31°23'41", 108°44'35"	6.83 ± 0.17 (whole rock)
E-5	Quartz Latite of Clanton	31°30'26", 109°02'06" unsurveyed	In progress

A summary of Quaternary and Late Pliocene age dates in New Mexico will be found in Kudo and others (1979). Important sources of data for this compilation were Bachman and Mehnert (1978) and Luedke and Smith (1978).

Geochemistry

WATER GEOCHEMISTRY

Introduction

Geochemical studies have consisted of the collection and analysis of all known thermal waters in New Mexico. Chemical data include major, minor and trace elements in addition to various isotopic ratios (Appendix 6, Tables 1-6). Further, non-thermal waters adjacent to geothermal anomalies have been analyzed for major and minor elements and isotopic ratios for comparison with the thermal waters. Finally, over 10,000 groundwater analyses from New Mexico and adjacent areas have been examined to complete the regional geochemical picture. Quantitative and qualitative geothermometers have been applied to these data in order to establish the location and potential of the state's resources. On the basis of the geochemical data, the state's geothermal resources have been ranked in the order of descending subsurface temperature estimates. Maps have been prepared showing the location of geothermal prospects with respect to various geological and geophysical parameters including heat flow, recent volcanic rocks, deep sedimentary basins and major Quaternary faults and continental lineaments.

Literature Study

The initial part of the geochemical program consisted of a massive search of the hydrologic literature for waters which, on the basis of their chemical constituents, appeared to be of thermal origin. The main source of data for this search is the U.S. Geological Survey multiple station listing computer file (WATSTORE), which contains chemical analyses of over 10,000 groundwaters for New Mexico and adjacent areas. Additional chemical data were obtained from

various state and federal files to fill in the gaps in the WATSTORE coverage. On the basis of these chemical data, quantitative geotemperatures (SiO_2 , Na-K-Ca) were calculated and plotted on maps at a scale of 1:1,000,000 (Figures 2,3). Additional maps were prepared for in situ temperature and total dissolved solids (Figures 4,5).

There are three reasons to include cold water geochemistry in a study aimed at regional appraisal of geothermal resources. The first is to establish background chemistry against which the hot-water geochemistry can be compared. Swanberg and Morgan (1979) have shown that there are regional trends in temperatures calculated using the SiO_2 and NaKCa geothermometers, and these trends need to be known in order to properly evaluate the significance of hot spring data.

A second reason is to locate new geothermal areas. Swanberg (1975) and Swanberg and Alexander (1979) have shown that it is possible to recognize a geothermal water or detect a geothermal component in waters even though the waters may be of normal temperature. The procedure requires the assumption that a geothermal water, migrating from a geothermal reservoir into a shallow aquifer, will cool physically more rapidly than it loses its geothermal chemical signature, an assumption that gains credence because the speed at which reequilibration occurs slows at colder temperatures. The procedure then is to apply the quantitative and qualitative geothermometers to whatever chemical data may exist in the literature and note regions that yield high geotemperatures. Regions giving high geochemical temperatures by three or more different geothermometers are likely geothermal prospects. A final reason to study cold waters is to locate areas where the groundwaters have high concentrations of boron, fluoride, etc. Geothermal resources in these areas may require special handling to insure that the environment is not adversely affected by geothermal development.

Figure 2. Subsurface temperatures in New Mexico and west Texas calculated using the silica geothermometer.

Figure 3. Subsurface temperatures in New Mexico and west Texas calculated using the NaKCa geothermometer.

Figure 4. Temperatures of wells and springs in New Mexico and west Texas.

Hot Spring Study

Concurrently with the literature study, a list of reported thermal springs and wells was compiled. Any water in excess of 30°C was considered to be thermal, the hottest of which are Sulphur and Turkey Creek hot springs and the hot wells in the southern Tularosa Basin and at Lightning Dock KGRA, all of which are above 70°C . The locations of the thermal waters are shown in Figure 6 and their locations, temperatures and geochemical temperatures are summarized in Tables 3-5. Nearly all hot springs and wells in the study area were visited, temperatures and geology recorded, and samples collected for chemical analyses. The sampling procedures are those described by Presser and Barnes (1974). An untreated sample was collected in a polyethylene bottle for analyses of the stable constituents. A second sample, acidified with HNO_3 , was collected in a polyethylene bottle for analyses of the unstable constituents such as silica, iron, arsenic, etc. A third sample was treated with zinc acetate for laboratory determination of hydrogen sulphide. A fourth sample, acidified with HNO_3 , was collected in a glass bottle for analyses of trace elements such as mercury which might be absorbed by a polyethylene bottle. The chemical constituents of the thermal waters including major, minor and trace elements are given in Appendix 6, Tables 2-5. All analyses were conducted at the State Soil and Water Testing Laboratory located at New Mexico State University using the procedure outlined by the Environmental Protection Agency (1971). The untreated samples were then forwarded to the University of New Mexico for isotopic analysis.

In addition to the thermal waters, several nonthermal waters were collected near each occurrence of thermal water. These waters, representing cold springs, wells and in some cases surface waters, were chemically analyzed for major and minor constituents only (Appendix 6, Tables 2-3). The purpose of

Figure 6. Locations of hot springs, hot wells and major geothermal areas in New Mexico. Basic data is given in Tables 4 and 5.

Table 3. Major Geothermal Areas Sampled

Name	Lat	Long	T _{surface}	T _{SiO₂}	T _{NaKCa}	T _{subsurface}
Valles Caldera*	35 43	106 32	87	177	234	240
Lightning Dock*	32 08.5	108 50	99	160	167	170
Guadalupe Area	35 30	107 15	35	156	177	170
Hillsboro Area	31 57.2	107 34.8	34	162	169	165
Columbus Area	31 45	107 30	31	135	195	✓ 155
Kilbourne Hole*	31 45	106 50	28	133	200	✓ 155
Lower Frisco*	33 15	108 47	49	132	148	150
Radium H.S.*	32 30	106 55.5	53	118	223	✓ 130
Ojo Caliente	36 18.3	106 03.0	56	122	161	130
Montezuma H.S.	35 39.2	105 17.4	59	122	140	130
Mamby's H.S.	36 31.6	105 40.6	41	116	168	✓ 125
San Diego Mountain	32 38	106 58	52	105	233	✓ 125
Mesquite-Berino	32 10.0	106 40.0	31	112	175	✓ 120
Las Alturas	32 15.0	106 46.0	63	109	179	✓ 120
Ponce de Leon	36 19.4	105 36.5	34	106	92	105
Truth or Consequences	33 08.1	107 15.2	45	96	180	✓ 100
San Ysidro	35 35	106 50	52	89	160	100
Derry Spring	32 47.6	107 16.6	33	83	156	✓ 100

Table 4. Additional Major Geothermal Areas from WATSTORE

Southern Tularosa Basin	32 05	106 05	71	--	--	-150
White Sands (Town)	32 25	106 25	54	114	-160	-150
North of Socorro	34 20	106 50	41	110	166	-150
Prewitt Area	35 260	107 53.0	46	-100	-200	-150
Jemez Reservoir	35 20	106 40	warm	-120	-150	-150
Lordsburg	32 13.7	108 30.7	33	91	151	-150

* KGRA

✓ Estimated subsurface temperature in the 150-200°C range of mixing models are applied to the silica data

Table 5. Major Low Temperature Geothermal Areas

Name	Lat	Long	T _{surface}	T _{SiO₂}	T _{NaKCa}	T _{subsurface}
Turkey Creek H.S.	33 06.5	108 29.0	74	117	68	L.T.
Gila Hot Sp.*	33 10	108 10	66	129	77	L.T.
Closson	35 15.5	108 19.4	61	95	51	L.T.
Fort Wingate	35 30	108 35	61	--	--	L.T.
Mimbres H.S.	32 44.9	107 50.1	58	107	75	L.T.
Faywood H.S.	32 33.3	107 59.7	54	97	78	L.T.
Tohatchi	35 55.3	108 34.7	39	66	82	L.T.
San Francisco H.S.	33 49.8	108 47.9	37	97	52	L.T.
Crown Point	35 41.6	108 08.4	37	60	80	L.T.
E. San Augustin Plain	34 00.5	108 05.5	35	108	53	L.T.
Socorro*	34 05.0	106 57.0	34	61	72	L.T.
Garton Well	32 46.8	106 09.0	34	63	100	L.T.
Cliff Area	32 52.6	108 35.0	31	85	53	L.T.

* KGRA

analyzing nonthermal waters is to establish background chemistry, against which the chemistry of the thermal waters can be compared and therefore more meaningfully analyzed.

On the basis of the chemical data, both qualitative and quantitative geothermometers were evaluated and the results form the primary method whereby each specific area is appraised for geothermal potential. The quantitative geothermometers are silica (Fournier and Rowe, 1966), sodium-potassium (Ellis, 1970), and sodium-potassium-calcium (Fournier and Truesdell, 1973). Geochemical temperatures calculated using the silica and Na-K-Ca geothermometers are given in Appendix 6, Table 1. The Na-K geothermometer is an older version of the Na-K-Ca technique and is not presented. The basic assumptions of these geothermometers are discussed by Fournier and others (1974) and can be summarized as follows:

- 1) temperature-dependent reactions in the geothermal reservoir control water chemistry;
- 2) water-rock equilibrium must exist within the geothermal reservoir;
- 3) minerals which supply the constituents upon which the geothermometers are based must exist within the geothermal reservoir;
- 4) re-equilibration must not occur as the water migrates from the reservoir to the sampling point; and
- 6) there must be negligible mixing with near surface waters of different chemical composition.

The qualitative geothermometers include low concentrations of calcium and bicarbonate in near neutral pH waters (Ellis, 1970), low ratios of magnesium to calcium (White, 1970), high ratios of sodium to calcium (Mahon, 1970), highest ratios of chloride to total carbonate ($\text{Cl}/\text{CHCO}_3 + \text{CO}_3$) (Fournier and Truesdell, 1970), and highest ratios of chloride to fluoride (Mahon, 1976). The basic data necessary to apply these geothermometers are given in Appendix 6, Tables 2-3.

Ranking Criteria

On the basis of the silica and NaKCa geothermometers, "best guess" subsurface temperature estimates have been prepared and listed in Tables 3 to 5 in order of descending geothermal potential. The criteria used in the subsurface temperature estimates is the same as employed by the U.S. Geological Survey in the preparation of Circular 726 (White and Williams, 1975). If the two geochemical temperatures are in good agreement, an approximate average is used. If there is a large discrepancy in the two geochemical temperatures, the lower value is taken. In some cases, mixing models have been employed. These cases are designated by a check mark in Table 3.

Several hot spring areas, including two KGRAs and Turkey Creek Hot Spring, do not yield chemical temperatures in excess of adjacent nonthermal waters. These areas are given a subsurface temperature of LT (low temperature) and are listed in Table 5 in order of descending surface temperature.

Geothermal Areas

The major geothermal areas in New Mexico are listed in Table 3 and shown in Figure 6. It is clear from Figure 6 that the vast majority of promising geothermal prospects in New Mexico are located within the Rio Grande rift, a tectonic province running north-south through the center of the state and containing the state's major population centers (Woodward and others, 1978).

Several prospects are located near the boundary of the Colorado Plateau, a boundary that is also associated with geothermal resources in Utah, Arizona and Colorado. A lesser number of promising prospects are located in the Basin and Range Province and the Colorado Plateau. There is no convincing evidence of any geothermal activity east of the Rio Grande rift. Nearly all geothermal prospects in New Mexico are located within the high heat-flow zone ($>100 \text{ mWm}^{-2}$; 2.5 HFU) delineated by Reiter and others (1975).

Although the data listed in Tables 3, 4 and 5 and Figure 6 are self explanatory, a few areas are worthy of special mention.

Valles Caldera. There appear to be three different types of thermal water in this area. Sulphur Springs is an acid sulphate-type water containing very little chloride and appears to represent effluent from the vapor-dominated part of a major geothermal system. Several other springs such as Jemez Springs yield geochemical temperatures in excess of 200°C and probably represent effluent from the liquid-dominated part of the same geothermal system. A similar co-existence of liquid and vapor dominated parts of a geothermal system has been observed by White and others (1971) in Yellowstone Park. A third type of thermal water, such as Spence Spring, consists of high quality waters yielding geochemical temperatures which are not above regional background. These waters are not part of the major geothermal system. For a further treatment of this area, see Trainer (1974, 1975) and Trainer and Lyford (1979).

Southern Rio Grande rift. There is so much geothermal water in the southern Rio Grande rift that it is difficult to delineate specific sites at the scale of Figure 6. A more detailed description of this area is given by Swanberg (1975). Most of thermal wells and springs give silica and NaKCa temperatures of about 115 and 200°C respectively. However, if mixing models are applied, both geothermometers give temperatures near 200°C . The hottest of these appear to be in the Radium Springs-San Diego Mountain area. Mixing models could not be applied to the Kilbourne Hole-Columbus areas because the wells have nearly the same temperature. The hot wells in the White Sands-Southern Tularosa basin area could not be studied because of limited access to the military land.

Socorro area. The warm springs in the Socorro KGRA do not show geothermal potential on the basis of their chemical constituents and are ranked far down the list of prospective geothermal prospects (Table 5). However, several wells to the north of the KGRA which were included in the WATSTORE file appear to be of thermal origin. This area is included in Table 4 .

Carlsbad area. Although there are no warm wells or springs in this area, several of the groundwaters yield very high geochemical temperatures. It is most likely that the NaKCa data are too high due to the presence of potash deposits, and the silica data are too high because of the presence of amorphous silica in several of the aquifers. However, this area is located on a major lineament and is included in Figure 2 for the sake of completeness.

Gila area. The Gila Hot Springs KGRA is given a subsurface temperature estimate of 125°C by the USGS (White and Williams, 1975). This estimate is supported by the silica geotemperatures but is not supported by the NaKCa geotemperatures, which generally fall in the 70-80°C range (Table 5). However, the Gila area is in a high silica region and the nonthermal waters (and in some cases the surface waters) also give silica geotemperatures as high as 110°C. There is no convincing evidence from water chemistry of high subsurface temperatures, and the Gila Hot Springs KGRA is listed in Table 5 with the other low-temperature geothermal resources.

Origins of Geothermal Areas

The major thermal areas in New Mexico are shown in Figures 7-10 along with other pertinent geothermal data such as young volcanic rocks, maar volcanos, deep sedimentary basins, regions of high heat flow and major continental lineaments. These figures reveal much about the origins and potential

Figure 7. Major geothermal areas in New Mexico and their association with deep sedimentary basins.

Fig. 8. Locations of major geothermal areas with respect to Quaternary tectonic activity and vulcanism. Geology from W. Seager and J. Callender (personal communication).

-LEGEND-

	Fault with hachures, cuts late Quaternary deposits. Hachure on downthrown block.		Quaternary volcanic rocks (< 4 m.y. old) dots indicate volcanic centers.
	Fault, dashed. Cuts late Pliocene or Pleistocene deposits (about 1-4 m.y. old). Ball and bar on downthrown block.		Anticlinal and synclinal post-Tertiary warps based on preliminary structure contours on top of Ogallala Formation in east-central part of state.
	Fault, solid line. A continuation of one of the above where clear evidence of later movement is not present.		Major Geothermal area.
	All faults dotted where concealed or covered.		Low temperature geothermal area.

Fig. 9. Detailed portion of the northwest part of Fig. 8.

Figure 10. Heat flow in New Mexico (from Swanberg, 1979).

applications of the geothermal resources. For example, several of the thermal areas such as Valles Caldera, Kilbourne Hole and the Guadalupe area are associated with recent volcanism and maar volcanos (Figures 8-9). The source of the geothermal energy for these areas is likely to be of magmatic origin. These areas are the most likely prospects for electricity production. Also, since magmatic activity is involved, environmental problems associated with hydrogen sulphide, mercury, arsenic, etc., are likely to be greater. Other thermal areas are not associated with recent volcanic rocks but are associated with deep sedimentary basins (Figure 7). Examples include the White Sands area (Tularosa basin), the Cliff area (Mangas Trench), and the Jemez Reservoir area (Albuquerque basin). These areas probably result from waters, heated by a moderate geothermal gradient (i.e., $\sim 40^{\circ}\text{C}/\text{km}$), which have ascended from great depth along major fault zones. Since these areas are likely to be associated with large volumes of water stored in sedimentary basins, their chief use may be geothermal desalination (for brackish waters), direct heat applications such as space heating or agricultural and industrial processes (fresh waters), or, if the waters are sufficiently hot and suitable cap rocks exist, for electricity generation.

Additional Low Temperature Resource Areas ($20\text{--}30^{\circ}\text{C}$)

The U.S. Department of Energy has established 20°C as the cutoff temperature for designation of geothermal waters; such low temperature waters may have applications in agriculture, heat pump applications and other uses. For the State of New Mexico, roughly half of all wells exceed 20°C , thus making the entire southern part of the state a proven geothermal resource area. In this report, only hot springs and wells in excess of 30°C are shown individually (i.e., Figure 4). Groundwaters in the $20^{\circ}\text{--}30^{\circ}\text{C}$ range are shown separately in Figure 11. The southwest-northeast contour shown in Figure 11

Figure 11. Map showing the locations in New Mexico where any well drilled into the water table should exceed 20°C.

denotes the approximate location of groundwaters exceeding 20°C. That is, any well drilled to the water table south of the contour will probably exceed 20°C, with the obvious exception of the high mountain areas such as the Sacramento Mountains. North of the contour, wells drilled to the water table will generally be colder than 20°C. Also shown in Figure 11 are the four major physiographic divisions of New Mexico. Figures 12 and 13 show the temperature of waters in these physiographic divisions. The temperature data in Figures 12 and 13 form the basis for drawing the contour shown in Figure 11. For the Basin and Range and southeast plains, 67 percent and 79 percent, respectively, of all groundwaters exceed 20°C. However, for the Colorado Plateau and the northeast plains, only 32.3 percent and 28 percent of the groundwaters exceed 20°C.

Conclusions

On the basis of the geochemical data, the following conclusions seem to be justified.

1. At least 7 and possibly as many as 20 discrete areas may have subsurface temperatures in excess of 150°C, sufficiently high for economic development of electricity (Tables 3, 4).
2. The vast majority of the high temperature-geothermal prospects are located within the Rio Grande rift, a tectonic province which includes the state's major population centers.
3. Several geothermal prospects such as the southern Tularosa basin are associated with large volumes of geothermal brine and are ideally suited for geothermal desalination.
4. Numerous geothermal prospects in western New Mexico consist of high quality, high temperature water but do not apparently have sufficient subsurface temperatures for electricity generation. These prospects appear ideal for direct heat utilization such as space heating and agricultural applications.

COLORADO PLATEAU

Average 16.81°C
 Deviation 8.41°C
 Samples 478
 Latitude 34-37°N
 Longitude 107.5-109°W

NORTHEAST PLAINS

Average 18.65°C
 Deviation 4.79°C
 Samples 194
 Latitude 35-37°N
 Longitude 103-105.5°W

Figure 12. Histogram of groundwater temperatures in the Colorado Plateau and the Northeast Plains.

BASIN AND RANGE

Average 21.88°C
 Deviation 4.20°C
 Samples 797
 Latitude 30-32.5°N
 Longitude 106-109°W

SOUTHEAST PLAINS

Average 22.21°C
 Deviation 4.84°C
 Samples 1600
 Latitude 30-33.5°N
 Longitude 103-105.5°W

Figure 13. Histogram of groundwater temperatures in the Basin and Range and Southeast Plains.

5. Nearly all groundwaters in southern New Mexico have temperatures in excess of 20°C , the minimum temperature designated by the U.S. Department of Energy for low temperature utilization. Industries requiring (or having the ability to utilize) such waters should find a nearly inexhaustible geothermal resource in southern New Mexico.
6. Two separate types of geothermal systems are recognized in New Mexico. Those of the more abundant type are located along the flanks of the deep sedimentary basins and owe their origin to deeply circulating groundwater which ascends to the surface along the tectonically active basin-bounding faults. Those of the less abundant type are associated with Quaternary igneous rocks and in part may be heated by magmatic activity.

(87/86) STRONTIUM MEASUREMENTS FOR SOME NEW MEXICO VOLCANIC ROCKS

Introduction

Volcanic rocks from several prospective geothermal areas in New Mexico were studied for their $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in order to attempt to establish background values for basaltic rocks (and associated rock types) and to assist in defining local zones of intense alteration.

Analytical Methods

Sr isotopic compositions were determined using a Nier-design, Nuclide 1290 12"-90° solid source mass spectrometer. Chemistry involved standard $\text{HF}:\text{HClO}_4$ dissolution, $\text{H}_2\text{O}:\text{HCl}$ digestion, and separation of Sr by ion exchange chromatography. $\text{Sr}(\text{Cl})_2$ was converted to $\text{Sr}(\text{NO}_3)_2$ by fusion in vycor and addition of HNO_3 . The Eimer and Amend Standard SrCO_3 (Lot 492327) was analyzed

seven times during the course of the investigation with $^{87}/^{86}$ (normalized to $^{86}/^{88} = 0.1194$) = 0.7080 ± 0.0005 (two sigma). Rb and Sr were analyzed by atomic absorption spectrophotometry using techniques modified from U.S. Geological Survey techniques by Mr. John Husler. The data are precise to ± 10 percent (one sigma).

Leaching of several samples (Table 6) was accomplished by addition to rock powder of successive aliquots of vycor-distilled 2N HCl. The leachate fraction was condensed to 5 ml and Sr separated by ion exchange chromatography. The insoluble residues were treated as whole rocks by the $\text{HF}:\text{HClO}_4$ technique described above.

Discussion

A summary of all Sr and Rb-Sr data is given in Table 6. The samples from the Mount Taylor volcanic field (Crumpler, 1977), with the exception of No. 75-1 (a mugearite), yield an average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7050 ± 0.0010 (one sigma), which is not different, within the limits of error, from samples of McCarty's flow reported by Brookins and others (1975), i.e., $X = 0.7051 \pm 0.0010$ (one sigma). For both suites of samples no correlation with total Sr or with total SiO_2 for $^{87}\text{Sr}/^{86}\text{Sr}$ was noted. For the samples from Mt. Taylor, however, there is a correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ and $\text{SiO}_2/\text{K}_2\text{O}$ (Brookins, unpublished manuscript).

The data are too few from San Antonio Mountain to form any conclusions, other than to note considerable spread in $^{87}\text{Sr}/^{86}\text{Sr}$, beyond analytical uncertainty. More detailed chemistry is needed before attempting an interpretation.

TABLE 6

Sr Isotopic and Rb/Sr Data

I. San Luis Basin (This report, Appendix 2; Zimmerman, 1978; Brookins and Zimmerman, 1980) *

<u>No.</u>	<u>87/86</u>	<u>No.</u>	<u>87/86</u>
TO-3	0.7045	BM-1	0.7059
V-3	0.7063	CCW-1	0.7054
G-1	0.7060	C-1	0.7076

II. Volcanics near Alum Mountain

GTV-302	0.7139	GTV-501	0.7068
GTV-405	0.7113	GTV-702	0.7354
GTV-406	0.7122	GTV-703	0.7059

III. Truth or Consequences volcanics (This report, Appendix 2; Warren, 1978; Brookins and others, 1980b)

BB-1	0.7051	BM-4	0.7057
BB-3	0.7042	CH-7	0.7044
MP-7	0.7073		

IV. San Antonio Mountain volcanic field (Eppler, 1976; Brookins and others, 1977b)

DE-5	0.7070	DE-19	0.7075
DE-80-R	0.7036	DE-327	0.7032
DE-440	0.7048		

V. Mount Taylor volcanics (Crumpler, 1977; Brookins and others, 1977a)

78-1	0.7056	109-1	0.7039
B23B	0.7053	66-1	0.7049
41-1	0.7061	FLJ-101	0.7047
75-1	0.7142	D-11	0.7047
134	0.7051		

Table 6 (continued)

VI. Albuquerque-Belen basin volcanics (Kasten, 1977; Brookins and others, 1980a)

No.	87/86 (insol. residue)	87/86 (whole rock)	87/86 (leach)	Rb(ppm)	Sr(ppm)
TS-7A (inner core)	0.7072	0.7080	0.7093	10	900
TS-7A (outer rim)	0.7070	0.7052	0.7096		
TS-7B	0.7070	0.7047 0.7046	0.7096	10	900
TP-11 (outer rim)	0.7037	0.7054	0.7061	46	800
TP-11 (inner core)	0.7061	0.7057	0.7063	46	800
LP-1	--	0.7060	--	20	1000
LP-2	--	0.7052	--	21	1000
LP-3	--	0.7047	--	21	1800
LP-4	--	0.7050	--	34	1500

For the two samples (TS-7A, TS-7B) from the Albuquerque basin (Kasten, 1977; Appendix 2, this report), the leaching experiments clearly show that Sr with high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, probably due to calcite, is leached from the samples. It is noteworthy that these two samples do not show calcite in thin section (J. Kasten, personal communication, 1977), but measurements of CO_2 must be made before ruling this out. In theory the whole rock data should plot at an intermediate position between leachate and insoluble residue data; they do for one sample (TS-7A) but not for the other (TS-7B). Sample heterogeneity is suspect. These particular experiments also demonstrate the necessity of conducting similar studies on every sample studied so as to truly show whether or not contamination is present in the form of calcite or other minerals.

The basaltic andesites from the Albuquerque basin yield internally consistent $^{87}\text{Sr}/^{86}\text{Sr}$ for the Los Lunas samples of 0.7052 ± 0.0004 (one sigma), but the Tome samples exhibit a range in $^{87}\text{Sr}/^{86}\text{Sr}$ for whole rocks from 0.7047 to 0.7080; insoluble residues probably yield a more realistic initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for these rocks of 0.7059 ± 0.0015 . Note, however, that the initial ratio for these samples from whole rock is 0.7060 ± 0.0012 . At this time it would be premature to attempt to distinguish between the Tome and Los Lunas initial ratio values except to state that the former exhibits more internal and possesses $^{*87}\text{Sr}$ which can be readily leached. Whether or not this indicates more incipient alteration at Tome relative to Los Lunas can only be verified by stable isotopic oxygen and carbon studies.

Additional discussion of strontium geochemistry of volcanic rocks of the Rio Grande rift will be found in Zimmerman and Kudo (1979a).

STABLE ISOTOPE GEOCHEMISTRY

Two types of stable isotope studies were undertaken in this project. First, a reconnaissance survey of the $^{18}\text{O}/^{16}\text{O}$ ratios in natural waters of New Mexico and adjacent west Texas was conducted to provide a regional data base. Samples included precipitation, surface water, and both thermal and non-thermal groundwater. Second, detailed oxygen isotope studies of target areas at Lightning Dock and at San Ysidro-Jemez Springs were conducted to provide information on the origin of the water, deep flow directions, water-rock interaction, steam separation processes, and the mixing of deep, thermal waters with shallow, cold waters at intermediate to shallow depths. Again, samples included precipitation, surface and groundwaters.

Most of the groundwater samples and some of the surface water samples from locations south of Socorro were collected by Swanberg (this report). Some supplementary groundwater samples, most of the surface water samples and all of the rainwater samples from south of Socorro were collected by G. P. Landis. All of the water samples from locations north of Socorro were collected by Landis.

The oxygen isotope analyses were performed on a standard 3-inch 60° sector Nier-type gas ratio mass spectrometer (Appendix 5). Data output was interpreted graphically and numerically by means of a digital integrator interfaced to a mini-computer. Gas samples of the waters were prepared by the $\text{CO}_2\text{-H}_2\text{O}$ equilibration method (Epstein and Mayeda, 1953). The precision of the data is better than ± 0.20 per mil. All data are reported in the permil notation:

$$\delta^{18}\text{O} = (R_x - R_{\text{std}}) / R_{\text{std}} \times 10^3$$

where $R_x = ^{18}\text{O}/^{16}\text{O}$ ratio in the sample and $R_{\text{std}} = ^{18}\text{O}/^{16}\text{O}$ ratio in Standard Mean Ocean Water (SMOW).

Eighty-six oxygen isotope analyses of seventy-six different water samples are reported here in tabular form (Table 7) and are also plotted by Kudo and others (1979) along with the regional contours generated by Taylor (1974). The

Table 7. Oxygen isotopy of New Mexico Geothermal Waters

Field #/ NMSU Lab #	Name	SMOW $\delta^{18}\text{O}_{\text{H}_2\text{O}}$	T _{meas}	T _{alk}	T _{SiO₂}	pH	Comments
I. LIGHTNING DOCK AND ANIMAS VALLEY, HIDALGO CO., NM							
rainwater	Lordsburg	-4.8426	NA	NA	NA	NA	El Charro's (7/12/75)
rainwater	N. Hidalgo	-4.7558	NA	NA	NA	NA	U.S. 70, ~ 5 mi. N. of Lordsburg (7/12/75)
rainwater	N. Hidalgo	-4.9487	NA	NA	NA	NA	<u>duplicate run</u>
16-8	Tom McCanta	-10.2563	83	NA	NA	NA	collected by Gary Landis
P 1	Road Well	-10.1808	23.0	38.1	81.2	8.20	Swallow Fork Peak Quad
P 2	Hot Well	-10.4857	85.0	172.9	160.1	7.71	Swallow Fork Peak Quad
P 3	Tom McCanta	-10.3398	81.0	168.5	198.2	8.16	Swallow Fork Peak Quad
P 4	Well	-10.4666	71.0	158.8	145.5	7.84	Swallow Fork Peak Quad
P 5	Well	-10.3335	22.0	60.0	94.2	8.08	Swallow Fork Peak Quad
P10	Hill Well	-10.3919	23.0	71.1	111.1	8.18	Swallow Fork Peak Quad
P13	Well	-9.7483	19.0	49.3	121.1	7.90	Swallow Fork Peak Quad
P14	Well	-9.6512	20.0	39.2	100.3	8.00	Swallow Fork Peak Quad
		-9.7943	NA	NA	NA	NA	<u>duplicate run</u>
P15	Well	-10.4664	24.0	57.4	85.0	8.07	Table Top Mtn. Quad
P20	Well	-10.2672	22.0	38.6	102.2	8.02	Cotton City Quad
		-10.1638	NA	NA	NA	NA	<u>duplicate run</u>
P22	Well	-9.5571	22.0	41.6	95.2	7.90	Table Top Mtn. Quad
P23	National Well	-9.7753	24.0	45.6	78.4	8.08	Swallow Fork Peak Quad
P24	Well	-10.3851	NA	156.0	161.0	7.92	Swallow Fork Peak Quad
P25	Well	-8.9143	23.0	50.1	85.0	8.35	Swallow Fork Peak Quad
		-8.9310	NA	NA	NA	NA	<u>duplicate run</u>
LD 1	Well	-11.2640	25.3	141.6	84.0	8.09	Lordsburg Quad
SW132		-11.2931					<u>duplicate run</u>
LD 2	Well	-11.5286	33.0	150.6	91.2	7.86	Muir Ranch Quad
SW133							

Table 7 (continued)

Field #/ NMSU Lab #	Name	SMOW $\delta^{18}\text{O}_{\text{H}_2\text{O}}$	T _{meas}	T _{alk}	T _{SiO₂}	pH	Comments
LD 3 SW134	Well	-9.3354	NA	61.3	95.3	7.48	Muir Ranch Quad
LD 4 SW135	Lone Hill Well	-11.1560	NA	57.6	82.5	7.94	Coyote Peak Quad
LD 5 SW136	Well	-10.1258	NA	94.3	99.1	7.82	Playas Quad
LD 6 SW137	Well	-9.1958	NA	35.8	89.5	7.92	Pratt Quad
LD 7 SW138	Well	-10.0033	24.4	21.3	99.5	7.82	Pratt Quad
LD 8 SW139	Well	-9.4838	21.2	18.9	97.2	7.57	Pratt Quad
LD 9 SW140	Well	-8.6278	18.7	44.7	99.5	7.39	Animas Peak Quad
LD10 SW141	Well	-8.8264	NA	57.6	90.9	7.31	Animas Peak Quad
LD11 SW142	Well	-9.0647	18.3	69.9	104.0	7.74	Cienega Springs Quad
LD12 SW143	Well	-8.0761	18.0	50.3	86.7	6.88	Cienega Springs Quad
LD13 SW144	Cienega Springs	-9.9562 -9.9265	17.0	56.2	90.9	7.00	Cienega Springs Quad <u>duplicate run</u>
LD14 SW145	Well	-9.5697 -9.5468	24.9	38.2	51.0	8.80	Cienega Springs Quad <u>duplicate run</u>
LD15 SW146	Well	-10.0668	20.6	38.6	99.5	8.11	Animas Peak Quad
LD16 SW147	Well	-10.0971	19.1	27.3	93.5	7.94	Animas Peak Quad
LD17 SW148	Well	-10.1135	21.6	23.3	95.9	8.00	Animas Peak Quad
LD18 SW149	Well	-9.6641	NA	35.1	94.8	8.15	Animas Peak Quad

Table 7 (continued)

Field #/ MMSU Lab #	Name	SMOW $\delta^{18}\text{O}$ H_2O	T _{meas}	T _{alk}	T _{SiO₂}	pH	Comments
<u>II. GILA AREA, GRANT CO., NM</u>							
rainwater	Silver City	-7.6907 -7.6564	NA	NA	NA	NA	8/15/75(G.P.Landi) <u>duplicate run</u>
16-9	Doc Campbells Hot Spring	-10.3566	NA	NA	NA	NA	
16-10	Gila R. Spring	-10.6788	65	NA	NA	NA	Ponded Pool at Spring (GPL)
16-11	Gila River	-9.0922	NA	NA	NA	NA	River below Spring (GPL)
J(W)-5	Lower Frisco Hot Spring	-10.9845	48.9	147.9	171.9	7.79	Wilson Mtn. Quad
Gila 20 SW150	Turkey Creek Spring	-10.8756	74.0	56.2	116.5	8.66	Canyon Hill Quad
Gila 21 SW151	Turkey Creek	-10.6881 -10.7455	28.0	53.8	101.8	8.33	Canyon Hill Quad <u>duplicate run</u>
MFG 2 SW162	Spring	-10.8974	31.0	34.6	102.7	8.07	Alum Mtn. Quad
MFG 3 SW163	Spring	-10.8558	37.0	19.4	107.2	8.09	Alum Mtn. Quad
MFG 4 SW164	Spring	-11.0773	36.0	31.4	107.5	8.15	Alum Mtn. Quad
<u>III. T OR C AREA, SIERRA CO., NM</u>							
GW-75-8A	Tingley Hospital	-9.7406	43	NA	NA	7.6	
GW-75-9	Tingley Hospital	-9.0524	21	NA	NA	9.3	at well collar in river
GW-75-14	Yucca Bath House	-9.6999	42	NA	NA	7.5	
<u>IV. RADIUM SPRINGS, DONA ANA CO., NM</u>							
B2	Radium Springs	-9.8837	53.0	223.4	118.1	8.16	

Table 7 (continued)

Field #/ NMSU Lab #	Name	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$ SMOW	T _{meas}	T _{alk}	T _{SiO₂}	pH	Comments
V. VAN HORN AREA, TEXAS							
TR2-2 SW224	Spring	-7.7041	17	-6.4	46.7	8.12	
TR2-11 SW233	Windmill	-9.2121	20	213.4	68.8	8.19	
VI. OJO CALIENTE AREA, RIO ARRIBA CO., NM							
J May 3	La Madera	-14.5856	NA	NA	NA	NA	atmospheric contamination probable
VII. SAN YSIDRO AREA, SANDOVAL CO., NM							
GW-75-18	Spring	-8.60	20			7.3	Hwy 44 - 3 mi west of San Ysidro
GW-75-19	Well	-9.39	53			6.8	Hwy 44 - 15 mi west of San Ysidro
GW-75-20	Stream	-8.79	28			8.2	Rio Salado
GW-75-21	Stream	-10.95	17			9.0	Paliza Creek
GW-75-22	Stream	-10.23	20			9.2	Guadalupe River
GW-75-23	Mound Spring	-10.40	74			7.0	Jemez Springs
GW-75-24	Stream	-9.68	21			NA	Jemez River, 29' from Mound Spring <u>duplicate run</u>
		-9.71					
GW-75-25	Pool Catchment	-10.07	65			NA	Jemez Springs
GW-75-26	Stream	-9.89	47			7.0	Soda Dam
GW-75-27	Spring	-11.80	32			8.7	Battleship Rock
GW-75-28	Spring	-11.17	41			8.8	Lower Spence Springs
GW-75-29	Stream	-10.00	NA			NA	San Antonio River
GW-75-30	Spring	-11.94	40			8.5	San Antonio Hot Spring
GW-75-31	Spring	-3.71	75			1.4	Sulfur Springs at bath
GW-75-32	Spring	-8.13	90			3.0	Steam Vent Pool above bath

results of the reconnaissance water survey are included in Appendix 6. The results of the detailed studies at Lightning Dock and San Ysidro-Jemez Springs will be discussed below.

Geophysics

REGIONAL MAPS

As noted above, overlays of regional geophysical data (Zilinski, 1976 a,b,c) were made for the tectonic map of the Rio Grande rift (Woodward, Callender and Zilinski, 1975). In addition, all geoelectric studies of the State were collected and analyzed. The geoelectric material was ultimately compiled for the State of New Mexico Geoscience Map Series (Jiracek, 1979).

ELECTRICAL TECHNIQUES

Introduction

The value of electrical methods in the detection and delineation of geothermal reservoirs has been recognized worldwide. This is evident by the variety of successful results reported in the Proceedings of the 1975 United Nations Geothermal Meeting (1976). In practice, the various electrical techniques give rise to different results, and consequently many controversies have arisen over the application of individual methods. The complexities of this problem have been recently debated at a workshop on the Evaluation of Electrical Methods in the Geothermal Environment (Ward, 1977). Our ultimate objective in electrical methods is to define the geoelectrical properties of a region and to infer geological (geothermal) significance from the results. The extent to which this objective is realized must rely on a combination of electrical field methods and interpretational procedures. Our electrical

exploration studies in New Mexico were accomplished using several artificial and natural source methods at various geothermal prospects in the State. We have made no effort to use every method at each site, although in some instances our results represent the most complete coverage available.

This summary report presents in later sections most of the pertinent data from these surveys and various degrees of progress toward interpreting the results. We expect considerably more progress in the interpretation of results leading to more definitive geothermal inferences.

Artificial Source Survey Methods

Direct current mapping. The bipole-dipole mapping technique (Keller and others, 1975; Stanley and others, 1976) has been used at all test sites in New Mexico to provide areal resistivity coverage and comparison with other electrical methods. The general technique has been the source of considerable criticism because of the difficulties in interpretation (Ward, 1977). Hence, a significant aspect of this report is the successful three-dimensional modeling of the bipole-dipole results at Las Alturas Estates using a method developed by G. Hohmann (Hohmann and Jiracek, 1979). Our results, when compared to other electrical methods and known geology, illustrate that the method provides valuable information.

We have applied the bipole-dipole technique in two variations of the total field mapping procedure: 1) the standard long-wire source, grounded at surface points approximately 2 km apart; and 2) one electrode positioned downhole, in the geothermal aquifer, and the other current contact at a remote surface site 3-4 km away. Through these current contacts was passed a square wave current of 5-40 A peak amplitude with periods varying from 5-20 seconds. The two-electrode current source is referred to as a bipole to distinguish it from the shorter

(10-100 m) voltage measuring electrode pair designated a dipole despite its finite length. To produce a total field apparent resistivity map, two dipole measurements are made at each receiver site. Such measurements are usually made as an orthogonal pair and at many (50-150) points surrounding the bipole source. In subsequent discussions of the mapping results, we will refer to the standard data using only surface electrodes as bipole-dipole mapping, whereas when using the downhole electrode, the term downhole-remote mapping will apply. In the latter case, when an additional electrode is energized on the surface near the wellhead, the results are designated as surface-remote mapping. The downhole-remote method is nearly identical to the mise-a-la-masse method long used in mining exploration (Parasnis, 1967). This technique utilizes a common reference electrode for all voltage measurements instead of the dipole pair. Bipole-dipole maps produced in this report plot values of total field apparent resistivity as defined by Keller and others (1975). The downhole-remote and surface-remote results present the commonly computed radial apparent resistivities (Merkel, 1971); total and tangential field values will be considered in later analyses. Results are presented as contoured values of apparent resistivity which are plotted at the receiver locations for this purpose. Interpretations discussed are largely qualitative with a constraint that they be compatible with the quantitative sounding results and known geology.

Direct current sounding. Direct-current, vertical electrical sounding (VES) uses standard Schlumberger and dipole-dipole arrays (Keller and Frischknecht, 1966) and a combination of asymmetric Schlumberger and equatorial arrangements (Zohdy, 1970). Apparent resistivity formulas and examples of Schlumberger VES in geothermal exploration are found in Zohdy and others (1973) and Stanley and

others (1976). Beyer (1977b) presents dipole-dipole geothermal surveys. In combining asymmetric Schlumberger with equatorial results, we have continued our policy (Jiracek and Smith, 1976) of plotting apparent resistivity versus effective spacing as defined by Zohdy (1970). Such plots yield equatorial sounding curves for layered earth that are identical to standard Schlumberger curves. There is no standard method for plotting asymmetric Schlumberger results; we have used the distance between the center of the voltage electrodes and the nearest current electrode as the abscissa of the sounding curve.

The relative merits of the various VES methods have been discussed by Keller and Frischknecht (1966) and more recently by Edwards (1977). Effective depth of exploration and depth resolution of VES methods depend on the various authors' definitions of these terms. Even so, array depth characteristics are quite different from lateral sensitivities. As a result, the choice of which electrode configuration to use in a given survey often is governed more by practical considerations. For example, the field logistics in combining VES with continuous profiling usually favor the dipole-dipole method. Also, equatorial soundings can be obtained simply as a bonus for positioning enough bipole-dipole mapping stations along the equator of the transmitting bipole.

Quantitative interpretations of the VES data are permitted by assuming one-dimensional (layered) earth for the individual soundings and two-dimensionality for the dipole-dipole results. Algorithms from Inman and others (1973), Zohdy (1973a,b; 1974), Madden and Swift (1969) and Dey and Morrison (1976) have been employed.

Natural Source Survey Methods

Magnetotelluric sounding. Magnetotelluric (MT) soundings at geothermal sites have provided geoelectric information to tens of kilometers depth by using

natural electric and magnetic micropulsation fields with periods as long as 1000 sec (Stanley and others, 1977). The method has recently experienced revitalized interest because of new instrumentation, sophisticated data processing and improved interpretational techniques. These advances contributed to the statement by Ward (1977) that the MT method "may be the most powerful technique available for geothermal exploration over large areas."

MT soundings at two locations in New Mexico were made using a three-component cryogenic magnetometer built by SHE Corporation (Appendix 5). Horizontal electrical fields were obtained in the usual fashion using grounded electrodes approximately 300 m apart. Both MT surveys were accomplished as cooperative programs, one with Geonomics, Inc. and the other with the California Institute of Technology. In each case the cooperating groups furnished the necessary recording capability. The basic data acquisition systems are described in the Albuquerque basin (COCORP) and Lightning Dock KGRA field investigation sections. Processing of the results thus far has used the standard tensor methods (Vozoff, 1972; Stanley and others, 1977). The common method of combining one-dimensional inversions (Bostick, 1977) at each MT site was used to produce a preliminary geoelectric section at the COCORP location.

Telluric profiling. The E-field ratio telluric method as conducted by Beyer (1977a) in Grass Valley, Nevada has been applied to a limited extent at Lightning Dock KGRA in New Mexico. The method employed a linear three electrode array to measure successive electric fields as the array was leap-frogged along the 4-km long survey line. Distance between array points was approximately 300 m; E-field ratios at 0.045 and 8 Hz were attempted to obtain a degree of depth discrimination. Beyer (1977c) recommended that the E-field ratio telluric method should replace the bipole-dipole mapping method in electrical

reconnaissance of areas of several hundred square kilometers in terrain where in-line station locations can be established. Our experience, although limited in the telluric method, does not dictate such a conclusive statement.

Self-potential profiling. The self-potential (SP) method has yielded qualified success in geothermal exploration (Corwin, 1976). The method requires careful measurement of the natural or spontaneous voltage between two surface points. Geothermal activity is thought to generate SP anomalies by thermoelectric coupling or by streaming potential generated by subsurface fluid motion. Conclusive research into the origins of the voltages (on the order of tens of mV and more) is considered essential before the method can be applied with any degree of reliability in geothermal exploration (Ward, 1977). We performed SP measurements at only one location (Lightning Dock KGRA), which were repeated for three successive daily readings along a 4-km profile.

New Mexico Study Sites

Electrical exploration methods were applied in the geothermal assessment of five sites in New Mexico (Figure 14). Table 8 lists each study site along with the extent to which each electrical technique was applied. Gravity surveys have been made at two sites by personnel from New Mexico State University as a part of our overall study.

Two sites, Rio Rancho and COCORP, are located in the Albuquerque basin of the Rio Grande rift (Figure 14). The Rio Rancho tests (Table 8) were undertaken strictly as a field trial in the geothermally promising rift environment. Its proximity to the University of New Mexico and the availability of deep (3367 m) drill hole information dictated its choice. The drill hole did not indicate a high-temperature geothermal potential since the bottom-hole temperature was reported as approximately 100°C. However, the sedimentary sequence and

Figure 14. Location of areas studied with electrical resistivity methods in New Mexico.

TABLE 8. Electrical exploration at New Mexico geothermal project areas.

PROJECT AREA	ELECTRICAL TECHNIQUE*			
	Artificial Source (Direct Current Resistivity)		Natural Source (Self-Potential, Telluric, Magnetotelluric)	
	Sounding	Mapping	Profiling	Sounding
Albuquerque-- Belen Basin				
1. Rio Rancho	Schlumberger- Equatorial Dipole (1)	Bipole-Dipole (2)		
2. COCORP Area	Schlumberger- Equatorial Dipole (4)	Bipole-Dipole (2)		Magnetotelluric (8)
Las Cruces Area-- Mesilla Basin				
3. Radium Springs KGRA	Schlumberger- Equatorial Dipole (3)	Bipole-Dipole (2)		
4. Las Alturas Estates	Schlumberger (2) Dipole-Dipole (2)	Bipole-Dipole (2) Downhole-Remote (1) Surface-Remote (1)		
Animas Valley				
5. Lightning Dock KGRA	Schlumberger- Equatorial Dipole (1) Dipole-Dipole (1)	Bipole-Dipole (2) Downhole-Remote (1)	Self Potential (1) Telluric (1)	Magnetotelluric (5)

*Value in brackets is number of profiles, soundings, or maps.

crystalline basement encountered in the borehole are common to the rift environment. The COCORP site (Figure 14) is located approximately 40 km north of the Socorro Peak KGRA. Studies in this area have taken advantage of the high resolution, vibroseis reflection data obtained by the Consortium for Continental Reflection Profiling (COCORP). A reflection "bright spot" identified by these measurements (Oliver and Kaufman, 1976) has been correlated with a magma body interpreted at 18 km depth using microearthquakes (Sanford and others, 1977). To probe depths of this order we have included magnetotelluric sounding in our work (Table 8).

Radium Springs KGRA (site 3, Figure 14) marks the location of historic thermal springs discharging water at about 85°C. Although the site is at the northern end of the Mesilla Basin in the Rio Grande valley, the water is discharged from a faulted rhyolite dike complex (Seager, 1975a).

Study area 4 in Figure 14 includes a private subdivision, Las Alturas Estates, where local drillers in the last 20 years have encountered hot water in a localized ($<1 \text{ km}^2$) area. The maximum water temperature reported by drillers was 45°C in a 108 m deep well (Summers, 1976). The Las Alturas area is on a pediment slope of the eastern edge of the Mesilla basin only a few kilometers east of New Mexico State University. This proximity has prompted a more extensive evaluation (Table 8) of the prospect for possible heating and cooling applications on the university campus.

Lightning Dock KGRA (location 5, Figure 14) is in the Animas Valley, a typical basin in the Basin and Range province of New Mexico. An irrigation well drilled in 1948 encountered steam and boiling water (101.5°C) at the top of rhyolitic rock at a depth of only 27 m. This promoted immediate interest in the area for commercial geothermal exploitation, including electrical power

generation. However, prior to 1977 when a greenhouse complex was begun, the anomaly provided only very limited domestic heating. The obvious importance of the Lightning Dock area resulted in a concentration of geological, geochemical and geophysical (Table 8) investigations by our group.

4. TARGET AREAS

Lightning Dock

GEOLOGY

Introduction

This section describes the results of geologic mapping during 1975 and 1976 in and around the Lightning Dock Known Geothermal Resources Area (KGRA), Pyramid Mountains and Animas Valley, Hidalgo County, New Mexico (Figure 15). It covers the geology of four $\frac{7}{2}$ -minute quadrangles (North Pyramid Peak, South Pyramid Peak, Swallowfork Peak, Tabletop Mountain). It also includes a preliminary report on mapping in the Peloncillo Mountains, southwest of the Lightning dock KGRA, which was begun in the summer of 1977 and was completed in 1978.

This section emphasizes the geological setting and structural control of the Lightning Dock geothermal anomaly. It deals mainly with the bedrock geology of the Pyramid Mountains and with projections of geologic trends from the mountains into the adjacent Animas Valley, where the hot wells of the Lightning Dock KGRA are located. It also deals briefly with regional trends that could affect the heat source and water circulation.

All K-Ar dates cited in this report are unpublished determinations made at the laboratory of P.E. Damon (University of Arizona) under NSF grant EAR 76-02590 (see Deal and others, 1978). S. G. Wells (University of New Mexico) contributed to the section on valley fill and G. P. Landis, T. J. Bornhorst and E. E. Erb (University of New Mexico) contributed fluid-inclusion data for hydrothermal fluorite. Major-element chemical analyses were made by atomic absorption spectrophotometric and wet chemical techniques by Gayle Lux

Figure 15. Location of the Lightning Dock KGRA (A), the mapped area (coarsely stippled, B) and other "areas classified as being valuable prospectively for geothermal steam and associated geothermal resources" (finely stippled; Grim and others, 1977). 1- Peloncillo Mountains, 2 - Animas Mountains, 3 - Pyramid Mountains, 4 - Coyote Hills, 5 - Little Hatchet Mountains, 6 - Big Hatchet Mountains, 7 - Alamo Hueco and Dog Mountains, 8 - Cedar Mountains, 9 - Apache Hills, 10 - Sierra Rica.

(University of New Mexico), supervised by John Husler.

Location

In 1948 boiling water at 101.5°C and hot rhyolite were encountered at 26.5 m in a water well drilled in the Animas Valley, in NE $\frac{1}{4}$ sec. 7, T.25S., R.19W., Hidalgo County, New Mexico (Figure 16). Since then, several more wells have been drilled. Their locations, shown on the U.S. Geological Survey Swallowford Peak 7 $\frac{1}{2}$ -minute quadrangle, are in the southwestern corner of New Mexico, about 25 km southwest of Lordsburg. The nearest settlement is Cotton City, about 7.5 km to the southwest. The well site is directly behind the house of the present owner, Thomas McCants of Cotton City. It can be reached by a graded road from State Highway 338, 4.5 km to the west (Figure 15).

The Animas Valley is typical of the Basin and Range province. Its interior drainage leads to three playa lakes north of I-10, about 16 km north of the hot wells. The playas are remnants of Pleistocene Lake Animas, which once was up to 20 m deep. The valley is about 18 km wide; the hot wells are 5 km from its eastern edge. To the west, the valley is bordered by the Peloncillo Mountains and to the east by the Pyramid and Animas Mountains. The Pyramid Mountains are the main subject of this report. Compared to other ranges in the region, they are low and deeply eroded; their highest point, Pyramid Peak, elevation 1,830 m, stands about 566 m above the floor of the playa. Annual precipitation at Lordsburg is about 24 cm and natural vegetation is sparse.

Since 1950, much of the Animas Valley has been irrigated for growing cotton, sorghum and pecans. Geothermal water and steam could find a market for heating greenhouses. The nearest town is Lordsburg, and the nearest industrial plant is the Phelps Dodge Corporation Hidalgo Smelter at Playas, N.M., about 40 km to the southeast.

Figure 16. Localities in the Animas Valley and Pyramid Mountains mentioned in the text. Heavy line outlines the Lightning Dock KGRA.

Previous Work

Previous publications on the geology of the Animas Valley include hydrologic reports by Schwennensen (1918), Spiegel (1957) and Reeder (1957). In 1978 a geomorphic study of the valley north of the hot wells was completed by H. L. Fleischhauer (Fleischhauer, 1978), a graduate student at the N.M. Institute of Mining and Technology. It has been extended south, to cover the hot well field, by Dr. Stephen G. Wells, University of New Mexico, as part of the present study.

The geology of the part of the Peloncillo Mountains directly west of the hot wells was covered by Gillerman (1958) and more recently by the separate studies of A. K. Armstrong and M. L. Silberman and of Harald Drewes and Charles W. Thorman (USGS, unpublished). Summary articles will be found in Callender and others (1978). The geology of the Pyramid Mountains to the east was covered by Flege (1958); the present report is a complete revision of Flege's work. The Lordsburg mining district, which adjoins our map area to the north, was mapped by Lasky (1938), Flege (1959) and recently by Harald Drewes (unpublished).

The geothermal anomaly was first described by Kintzinger (1956) and mentioned later by Summers (1965 a,b,c, 1970, 1972; Summers and others, 1969). Renner and others (1975) identified it as one of only two known hot-water convection systems in New Mexico in which indicated subsurface temperatures exceed 150°C (the Valles caldera is the other). A brief report on geophysical studies, carried out concurrently with our geologic mapping, was published by Jiracek and others (1977). Low-temperature fluorite-manganese veins, which seem to be related to the geothermal anomaly, were described by Elston (1963, 1965).

Summary of Geology

The southern two-thirds of the Pyramid Mountains have been interpreted as a segment of an Oligocene ash-flow tuff cauldron, elongated to the northwest.

The name Muir cauldron, used here for the first time, is derived from the Muir Ranch, a pioneer ranch that covers parts of the Pyramid Mountains. Much of this report deals with the documentation of the Muir cauldron. It is too old to be considered a heat source for the Lightning Dock KGRA, but the modern geothermal anomaly seems to be structurally controlled by the intersection of its ring-fracture zone with a later, and currently active, Basin and Range fault. Hydro-thermal alteration is widespread in the Pyramid Mountain section of the Lightning Dock KGRA but is probably related to the Muir cauldron, not the modern geothermal anomaly. Contrary to previous investigators, we have found no evidence for post-Oligocene rhyolitic volcanism. We have found evidence for widespread fault-controlled hot-spring activity within the past 20 m.y. The geothermal anomaly may be a relict of this activity. Quaternary basaltic volcanism is more widespread in the region than was previously supposed.

Stratigraphy

The stratigraphy of the southern part of the Pyramid Mountains is best defined in terms of the development of the Muir cauldron. Pre-cauldron rocks consist of isolated exposures of Pennsylvanian (?) and Cretaceous sedimentary rocks and late Cretaceous and (or) early Tertiary basalt and Tertiary andesite. The felsic rocks of the cauldron have been included in the Pyramid Mountains Volcanic Complex, which formed in two stages. A later group of post-cauldron ash-flow tuffs and basaltic flows has been designated as the Rimrock Mountain Group. The ash-flow tuffs of the Rimrock Mountain Group originated beyond the Pyramid Mountains. Some of them seem to have come from centers in the Animas Mountains to the south (Elston and Erb, 1977), others from unknown sources. In general, the volcanic rocks of the Pyramid Mountains have calc-alkalic affinities. Rhyolite ash-flow tuffs, lava flows and breccias are the most

abundant rock types.

Valley-fill sediments younger than, or concurrent with, Basin and Range faulting and basaltic lava flows constitute the youngest rocks of the region. See Appendix 3 for a detailed description of the stratigraphy.

Summary of Oligocene-Recent Geology and History

The major post-Eocene geologic events that affected the Lightning Dock region are summarized here (from Deal and others, 1978). For additional information, see Deal and others (1978), Elston and others (1979) and Appendix 3.

Mid-Tertiary volcanism began with eruption of poorly dated andesite flows and breccias, as in many other parts of the Basin and Range Province. These were succeeded, between about 37 and later than 24 m.y., by quartz latite to rhyolite ash-flow tuffs, which erupted from at least nine known or suspected central cauldrons. There is a general progression (with some irregularities and reversals) in the succession of rock types. The earliest ash-flow tuffs tend to be crystal-poor quartz latite. They were generally followed by crystal-rich quartz latite ash-flow tuffs (phenocrysts of plagioclase, quartz, sanidine, biotite, hornblende and more rarely, augite), and these were succeeded by relatively crystal-poor quartz-sanidine rhyolite tuffs with little or no plagioclase or biotite. Flows of dark andesite and latite, basaltic andesite and basalt are locally interlayered with ash-flow tuffs. They are not as abundant as in the Mogollon-Datil field farther north (Elston and Northrop, 1976; Chapin and Elston, 1978), but they have a wide stratigraphic range.

Latite-to-rhyolite domes and lava flows are common, especially in the ring-fracture zones of cauldrons. The cauldrons vary widely in size, internal structure and depth of erosion. Some seem to have formed as a result of a single eviscerating eruption or several closely spaced eruptions, while others were the site of many eruptions separated by intervals of sedimentation or lava filling. Some resurged, others did not. In some, stocks of quartz monzonite porphyry were emplaced in the subsided cauldron block during a resurgent magma pulse.

Toward the end of mid-Tertiary volcanism, shallow sedimentary basins had formed. As a result, basin-fill conglomerate is interbedded with the undated tuff of Dutchman Canyon in the Peloncillo Mountains and with the upper tuffs (also undated) of the Rimrock Mountain Group of the Pyramid Mountains.

The O.K. Bar Conglomerate of Zeller (1967) overlies the youngest rhyolitic rock of the Animas Mountains. It is not known whether these conglomerates are thicker in the present basins than in the ranges, because they are exposed only in the ranges. Consequently, it is not known whether their accumulation was influenced by present Basin and Range structures.

At the northern end of Hidalgo County, the Gila River has cut into fill of the Animas Valley. The earliest post-rhyolite valley-fill sediments are bedded sandstone, in contrast to over-lying coarse fan material derived from Basin and Range fault scarps. The fine-grained fill is interbedded with basaltic andesite dated at 20.9 ± 1.5 m.y. (Elston and others, 1973). This date is as close to the beginning of Basin and Range faulting as one can get with present data. Basin and Range faulting continues into the present. There are scarps in Holocene valley fill on both sides of Animas Valley and in San Simon Valley (Reeder, 1957; Gillerman, 1958).

There is at present a gap in dated rocks between early Miocene and Pleistocene. The youngest valley-fill sediments in the Animas, San Luis, Playas, Lordsburg and Hachita valleys are late Pleistocene to Holocene lake beds, stream deposits and alluvial fans. A Pleistocene basalt flow (0.5 ± 0.03 m.y.) in the Animas Valley erupted from a cone in NE $\frac{1}{4}$ sec. 15, T.28S, R.20W. Another cone is in San Simon Valley, near Rodeo (NE $\frac{1}{4}$ sec. 32, T.28S., R.21W.) and four more are about 9 km farther south, in W $\frac{1}{4}$ sec. 30, T.29S., R.21W. The occurrences near Rodeo seem to be a northern extension of the San Bernardino volcanic field of southeastern Arizona.

The main Basin and Range border faults truncate all earlier structures, including ash-flow tuff cauldrons. In general, the trends of truncating Basin and Range faults are parallel to the trends of the present mountains, northerly in the western part of Hidalgo County (Peloncillo, Guadalupe, Pyramid, Animas, Whitewater and Little Hatchet mountains) and northwesterly in the eastern and northern part (Coyote Hills, Apache Hills, Sierra Rica, Big Hatchet and Alamo Hueco mountains and the area along the Gila River). Some of the faults that formed the collapse of Oligocene cauldrons and during Laramide activity moved again during Basin and Range activity.

Veins

Veins of several ages occur in the Pyramid Mountains. Northeast- and west-trending veins in secs. 1 and 2, T.24S., R.19W., are part of the Pyramid (or Leitendorf) subdistrict of the Lordsburg mining district, which has yielded between \$550,000 and \$600,000 in silver and copper (Elston, 1965). The veins were emplaced in the aphanitic member of the Cretaceous or early Tertiary

basalt; the porphyritic member is not known to be mineralized. Mineralization may be related to the Laramide Lordsburg granodiorite porphyry stock.

A second period of mineralization seems to be associated with the formation of the Muir cauldron. Mineral production has been negligible. Pyritization is widespread in rhyolite of Jose Placencia Canyon and in tuff of Woodhaul Canyon, especially in Woodhaul Canyon and in the Jose Placencia Canyon. Veins which carry pyrite and traces of stibnite have been prospected in sec. 7, T.25S., R.18W. They were emplaced in andesite of Holtkamp Canyon and tuff of Woodhaul Canyon. In SE $\frac{1}{4}$ sec. 17, T.25S., R.18W., a northwest-trending vein has been prospected for copper and silver. It is controlled by a dike of rhyolite of Jose Placencia Canyon, emplaced in andesite of Holtkamp Canyon. Copper stains occur at the margin of a northeast-trending rhyolite dike in SW $\frac{1}{4}$ sec. 2, T.24S., R.19W. Near the probable cauldron margin in S $\frac{1}{2}$ sec. 23, T.25S., R.18W., a northwest-trending fault controls a prominent quartz vein, about 1.6 km long.

A third period of mineralization resulted in veins, mostly northwest- or north-trending, which carry fluorite, psilomelane, black calcite and white calcite. Within the mapped area they have been worked for fluorspar and are located in secs. 15 and 23, T.25S., R.19W., and in sec. 2, T.24S., R.19W. The Doubtful (or Animas) mine, at the foot of Lightning Dock Mountain in sec. 15, T.25S., R.19W., is the most important fluorspar property in the southwestern corner of New Mexico. Past production has been small (\$40,000 to \$60,000), but General Chemical Corporation purchased the property after a drilling program and is holding it for future reserves. The mine is about 5 km east of the geothermal anomaly. Mineralization is Miocene or younger and may be related to the hydrothermal system that has been tapped in the Lightning Dock KGRA. This is discussed below in more detail.

Quaternary Deposits

Quaternary surficial materials of the Animas Valley consist of piedmont and valley-floor deposits. Piedmont deposits are mainly coalescing Holocene and Pleistocene alluvial fans and pediment deposits. Piedmont deposits also include modern or active wash sediment, which originated within the interior of the Pyramid Mountains and was deposited on the piedmont surface. Since the rhyolite chips recovered from the McCants hot wells are all of one rock type, apparently derived from bedrock rather than from boulders, the piedmont deposits near the wells can be no more than about 25 m thick. In the southwestern part of the mapped area, inselbergs rise through the piedmont deposits, suggesting that here also their thickness is not great.

Valley-floor deposits are fluviodeltaic deposits associated with ancient Lake Animas, as well as modern eolian deposits (coppice dunes and sand blankets) and active sheetwash deposits. The valley-floor deposits are much thicker than the piedmont deposits but their thickness is unknown. Water wells do not penetrate them and the records of wildcat wells for oil and gas have not been released.

The Quaternary piedmont deposits have been displaced by the Animas Valley fault, probably during the late Pleistocene or early Holocene. Vertical offset of old fan surfaces, which have well-developed soil horizons, is found over a distance of 16 km. The fault scarp is subparallel to the mountain front and is sinuous. Nearly 5 m of vertical relief can be measured locally.

Geomorphology and Neotectonics of Lower Animas Valley

The primary purpose of the geomorphic investigation was to evaluate late Tertiary and Quaternary faulting in the basin-fill deposits of the lower Animas Valley. Emphasis was placed on determining the stratigraphic sequence of

alluvial basin fill. Field investigations were concentrated in the lower Animas Valley where previous Quaternary(?) faults had been mapped.

A summary of results is given below.

1. The first part of this study was a reconnaissance of the stratigraphy of the surficial deposits, concentrating on the fill of the piedmonts (fan-pediments); the axial basin playa complex has been detailed by Fleischhauer (1978). The tentative stratigraphy of Quaternary surficial deposits is:

Youngest	Qal - fresh sands and gravels along active channels.
	Qf ₃ _a - unweathered, poorly-sorted silts, sands and gravels forming alluvial fans at the base of fault-line scarps.
	Qf ₃ _b - slightly weathered, moderately-sorted, fine sands, silts and clays forming fine-grained alluvial fans. Sediments deposited by sheet flow conditions at toe of older alluvial fans (Qf ₂).
	Qf ₂ - Weathered, poorly sorted silts, sands and gravels forming coarse-grained alluvial fans. Desert varnish shows light to moderate development and desert pavement is poorly developed.
	Qf ₁ - Heavily varnished gravels forming desert pavement developed on alluvial fan and(or) pediment.
	Qsa - Saline deposits of a chalky-gypsiferous composition with indurated hard pan at top of unit.
	Qt1 - Vesicular, olivine basalt flow (0.511 ± 0.03 m.y.; Deal and others, 1978)

2. The major faults in the lower Animas Valley are:

- a. Weatherby Canyon Fault: complex of en echelon fault line scarps paralleling eastern flank of the Peloncillo Mountains.

Evidence for faulting and tectonic instability:

- (1) linear zone (scarp) characterized by topographic relief transecting surficial deposits of varying age;
- (2) deposition of alluvial fans at base of scarp;

- (3) accelerated erosion of trunk and tributary drainage lines up slope from the scarps;
- (4) juxtaposition of Qf_{3b} and Qsa along vertical plane;
- (5) intersection of scarp with QTl and vertical and horizontal offset on lava; and
- (6) burying of the oldest fan deposits by Qf_2 and segmented longitudinal profile of piedmont slope.

Fault description: normal, maximum vertical displacement 2 m; strike = $N10^{\circ}E$; dip = greater than $80^{\circ}E$.

- b. Lightning Dock fault: complex of sinuous and en echelon fault line scarps paralleling west side of Pyramid Mountains.

Evidence for faulting is not as strong as for Weatherby Canyon fault, but some field criteria indicate tectonic instability:

- (1) linear zone (scarps characterized by topographic relief which is less steep than Weatherby Canyon scarps); and
- (2) linear juxtaposition of young and old soils; younger soils (torrefluvents) and older soils (haplargids/calciorthids) form anomalous soil boundary (i.e. linear and parallel to mountain front).

Geologic Structure

Pre-Oligocene structure. Pre-Tertiary structures are not exposed in the southern part of the Pyramid Mountains. Regionally, northwest-trending thrust faults, folds, strike-slip faults and normal faults of Sevier and (or) early Laramide age have been mapped in the Peloncillo, Animas, Little and Big Hatcher Mountains and in the Apache Hills and Sierra Rica. The northeast and west trends of veins in the Pyramid subdistrict are characteristic of late Laramide (late Paleocene to early Eocene) veins throughout this part of New Mexico.

Oligocene structure.

Development of Muir Cauldron

Mid-Tertiary structures are dominated by the Muir cauldron. It seems to be an elongated structure; its long axis strikes northwest, roughly parallel to

the regional trend of pre-Tertiary basement structures. The caldera wall and ring-fracture zone have been preserved only on part of its northeastern side. Two possible scenarios could explain the structure of the cauldron. The steps of the first scenario are as follows:

- (1) Eruption of minor amounts of ash-flow and of early ring-fracture domes.
- (2) Main-stage ash-flow tuff eruptions and caldera collapse. Intense hydrothermal alteration.
- (3) Late-stage ash-flow tuff eruptions and continued caldera collapse.
- (4) Intrusion of composite stock, probably as part of a resurgent magma pulse. The timing of this event relative to stages 5 to 7 is unknown.
- (5) Eruption of inner set of ring-fracture domes and flows.
- (6) Eruption of outer ring-fracture domes and flows and associated tuff deposits; partial filling of moat by conglomerate, and lake deposits.
- (7) Burial of the Muir cauldron by rocks of the Rimrock Mountain Group. The tuff members originated in centers beyond the Pyramid Mountains; at least one basaltic andesite member seems to have come from a vent in the ring-fracture zone.
- (8) Basin and Range faulting. The Muir cauldron was truncated to the east and west by north-trending normal faults, which border the Animas and Playas Valleys, respectively. Internally, faults related to caldera formation were reactivated. The entire cauldron was uplifted into a broad northwest-trending arch (Figure 17). The Rimrock Mountain Group was broken by a mosaic of faults and stripped from the center of the cauldron. It is now preserved only in the moat and outside the inner cauldron walls.

Figure 17. Tectonic map of the southern Pyramid Mountains. Cross-ruled pattern indicates the intersection between the Animas Valley fault and the ring-fracture zone of the Muir cauldron. It is considered most favorable for geothermal exploration.

By this scenario, the ring-fracture domes of stages 5 and 6, as well as the intrusions of stage 4, could be part of a resurgent magma pulse. By the second scenario, stage 4 is the only resurgent pulse and occurred after stage 7. According to this interpretation, the faults that break the Rimrock Mountain Group into a mosaic were formed during resurgent doming, as their pattern suggests. Reactivation during stage 8 would then have played a lesser role. The second scenario requires that the source volcanoes of the Rimrock Mountain Group were active before the Muir cauldron became extinct. Burial of the Muir cauldron by rocks of the Rimrock Mountain Group occurred subsequent to collapse but prior to resurgence. Accurate radiometric dates may decide between the two scenarios.

Compared with other well-studied cauldrons of southwestern New Mexico, such as the Mount Withington, Emory or Bursum, the Muir cauldron is small, shallow and highly complicated. Most of the complications arise from slumping of the cauldron walls and the accumulation of chaotic breccias on the cauldron floor. Possibly there were intermittent ash-flow tuff eruptions of relatively small volume rather than a single catastrophic eruption. The structure of the Muir cauldron will be described in some detail, to document the interpretation that the hot wells of the Lightning Dock KGRA are partly controlled by its ring-fracture zone. The interpretation has a large element of uncertainty, because continuous exposures occur only in the Pyramid Mountains. Structures beneath the Animas Valley must be inferred from exposures in isolated hills.

Geometry of Muir Cauldron

General structure: The Muir cauldron conforms to the pattern of cauldrons described by Smith and Bailey (1968), in that it consists of (1) an inner cauldron in which thick fill of ash-flow tuff accumulated, bordered by a

collapsed caldera wall, and (2) three zones of ring-fracture domes, flows and moat deposits outside the caldera wall (Figure 18). Of the three zones, one is earlier than the main cauldron fill and two are younger.

The inner cauldron has been warped into a broad northwest-trending arch. The outcrop of the composite stock and the chief area of alteration is west of the axis of the arch. The relative roles played in the formation of the arch by resurgent doming and by later Basin and Range faulting has not been determined. The general fault pattern within the inner cauldron (Figure 17) resembles that of the resurgent domes described by Smith and Bailey (1968).

The cauldron has been broken by an en echelon set of northwest-trending longitudinal faults (Swallowfork, Silver Tree, South Pyramid and China Pond faults) and by northeast-trending transverse faults (Mansfield-Rockhouse, Jose Placencia, Lightning Dock, Rainbow and Pinkey Wright-Elephant Back faults; Figure 17). The south Pyramid fault may be the eastern margin of a longitudinal graben; a set of poorly defined faults about 3 km to the west may form its western margin.

Inner cauldron: Between the Rainbow and Pinkey Wright-Elephant Back fault zones, the structure of the inner cauldron is relatively simple. An outcrop belt of pre-caldera rocks (andesite of Holtkamp Canyon) marks the axis of the resurgent(?) arch; caldera fill (tuff of Woodhaul Canyon) dips gently away on either side. The caldera fill is over 425 m thick and homogeneous. The Holtkamp Canyon-Woodhaul Canyon contact is the caldera floor. South of the Pinkey Wright-Elephant Back fault zone, rocks of the Muir cauldron are covered by rocks of the Rimrock Mountain Group. The base of the Rimrock Mountain Group is next exposed in the Threemile Hills, where rocks related to the Muir cauldron are absent. The southern and southwestern caldera wall must run between the

Figure 18. Structural elements of the Muir cauldron. Hachured line shows approximate limit of inner caldera fill (tuff of Woodhaul Canyon, tuff of Graham Well). Roman numerals denote successive ring-fracture zones:

- I (vertical lines) pre-collapse domes and flows of rhyolite of Jose Placencia Canyon.
- II (stippled) post-collapse domes and flows of latite of Uhl Well.
- III (cross hatched) post-collapse domes and flows of rhyolite of Pyramid Peak.

Crosses denote present distribution of Rimrock Mountain Group.

Pinkey Wright-Elephant Back fault and the Threemile Hills. The inferred China Tank fault has approximately the right position; it also marks the border between complex structures in the southern end of the Pyramid Mountains and simpler structures of outlying hills.

North of the Rainbow fault, structures are much more complicated. The tuff of Woodhaul Canyon thins and increasingly takes on the aspect of a caldera-collapse megabreccia, in the sense of Lipman (1976). The caldera apparently became enlarged toward the north by slumping, beginning during eruptions of the tuff of Woodhaul Canyon. The northern end of the caldera collapsed during eruption of the tuff of Graham Well; the tuff of Woodhaul Canyon is absent there. The scalloped outcrops of tuff of Graham Well are intercalated with slices of andesite of Holtkamp Canyon. At least part of the andesite appears to have slid off the northern segment of the caldera wall. The area north of the Jose Placencia fault zone seems to be outside the inner cauldron; neither the tuff of Woodhaul Canyon nor the tuff of Graham Well extend into it.

Ring-fracture zones: The three successive ring fracture zones, marked by alignment of felsic domes, are shown on Figure 18. Zone I formed before eruption of tuff of Woodhaul Canyon and caldera collapse; Zone II and Zone III formed later. Zone I overlaps slightly with the inner cauldron, in the vicinity of Lightning Dock Mountain.

Only the northeastern third of the ring-fracture zones is exposed; the rest is hidden under the Playas and Animas Valleys. In the oldest proposed cauldrons elsewhere in southwestern New Mexico, ring-fracture domes and associated deposits developed only on one side. The Goodnight-Cedar Hills depression (Seager, 1973) and the Crosby Mountain depression (Bornhorst, 1976) are examples. It is not known whether the Muir cauldron is another.

Beyond the ring-fracture zone, rocks of the Muir cauldron (Pyramid Mountains Volcanic Complex) are absent. The ring-fracture zone extends only a short distance north of the mapped area. Its extent under the Playas Valley is unknown. In the Animas Valley, its outer limit must lie between the Threemile Hills and the Pyramid Mountains. If correlation of the rocks of Table Top Mountain with rocks of the Pyramid Mountain Volcanic Complex is correct, the outer limit of the ring-fracture zone must continue between Table Top Mountain and the small hills of unassigned rhyolite and Paleozoic limestone northwest of the Threemile Hills. Projected north, the outer limit of the ring-fracture zone runs west of the hot wells of the Lightning dock KGRA.

The placement of the hot wells of the Lightning Dock KGRA within the ring-fracture zone of the Muir cauldron is supported by cuttings from the McCants wells. They seem to show mingling of rocks from the Pyramid Mountains Volcanic Complex with clastic material from other sources.

Post-Oligocene structure. Many faults of the Pyramid Mountains displace rocks of the Rimrock Mountain Group; they were active after the formation of the Muir cauldron. This period of faulting cannot be dated locally, but throughout southwestern New Mexico cauldron structures were reactivated by early stages of Basin and Range faulting. Where dated, Basin and Range faulting began after 21 m.y. and only minor movements occurred after 6 m.y. (Elston and others, 1976).

All rocks and structures of the Pyramid Mountains are truncated abruptly by north-trending faults on both sides of the range. Movement on these faults resulted in the present Basin and Range topography. On the east side of the Animas Valley, the Animas Valley fault, which cuts Quaternary piedmont deposits, has already been described. The hot waters of the Lightning Dock KGRA seem to be controlled by the intersection of this fault and the ring-fracture

zone of the Lightning Dock KGRA. This and other Quaternary faults of the Animas Valley were described in more detail by Reeder (1957) and Gillerman (1958).

Note on Peloncillo Mountains

Summary. The segment of the central Peloncillo Mountains directly west of the Lightning Dock KGRA consists of Precambrian granite, Paleozoic through Cretaceous sedimentary rocks and Tertiary intrusions. The entire area is a complex west-trending arch, overlapped on the north and south sides (near I-10 and U.S. 80, respectively) by Tertiary volcanic rocks. Mineralization occurred in Oligocene time (Gillerman, 1958; Carten and others, 1974; Todd and others, 1975).

Because of current work by members of the U.S. Geological Survey (Harald Drewes, Charles W. Thorman), we did no mapping in the central part of the Peloncillo Mountains. By analogy with other areas of southwestern New Mexico, it is possible that the arch of mineralized pre-Tertiary rocks is the floor of another cauldron complex and that its ring-fracture zone could pass through the vicinity of the Lightning dock KGRA.

During the summer of 1977, we began mapping a segment of the southern Peloncillo Mountains, between $31^{\circ}30'N$ and $32^{\circ}N$. This part of the range has the aspect of a ring-fracture zone of a cauldron complex, as yet unnamed (see Deal and others, 1978). Ash-flow tuff cauldron fill appears at the western foot of the range and has also been found in the Chiricahua Mountains of Arizona. The cauldron is too far south to affect the Lightning Dock KGRA. However, ranchers report occurrences of warm water in wells of this region, especially in the San Simon Valley near Rodeo, N.M.

Basalt volcanos. The U.S. Geological Survey Geologic Map of New Mexico (Dane and Bachman, 1965) shows a patch of Quaternary basalt off the western foot of the Peloncillo Mountains, in the San Simon Valley, just east of Rodeo, New Mexico. As far as we know, no description has ever been published. We examined this occurrence and found it to be an olivine-bearing basalt flow that issued from a spatter cone in NE $\frac{1}{4}$ sec. 32, T.28S., R.21W. The flow lies on young alluvial fan deposits but is partly buried by about 2 m of fan material (Figure 19). Four more basalt cinder cones and associated flows, not shown by Dane and Bachman (1965), were found about 9 km farther south, in W $\frac{1}{2}$ sec. 30, T.29S., R.21W. Their state of degradation suggests that they are Pleistocene, not Holocene. The rocks seem to be alkali basalt. Additional occurrences of Plio-Pleistocene basalt have been found in the southern Animas Valley by E.E. Erb (personal communication).

Several occurrences of basalt were found by Harald Drewes, U.S. Geological Survey (personal communication, March 6, 1978). In the northern Peloncillo Mountains, small intrusions and cinder cones of basalt occur in NE $\frac{1}{4}$ sec. 7, SW $\frac{1}{4}$ sec. 8, and NE $\frac{1}{4}$ sec. 32, T.23S., R.21W. A K-Ar whole-rock date of about 6.1 m.y. was determined by R.F. Marvin, U.S. Geological Survey (written communication to Harald Drewes, February 1978). Dikes of similar lithology were found in the Lordsburg mining district, in SE $\frac{1}{4}$, SW $\frac{1}{4}$ sec. 9 and SW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 16, T.23S., R.18W.

Until now, only two basaltic centers were known in this region: the large San Bernardino field in the southeastern corner of Arizona (Lynch, 1978) and a single cone in the Animas Valley, in NE $\frac{1}{4}$ sec. 15, T.28S., R.20W. A lava flow from this cone yielded a whole-rock K-Ar date of $140,000 \pm 20,000$ years (R.F. Marvin, written communication to Harald Drewes, February 1978). The newly—

Figure 19. Distribution of Plio-Pleistocene basalt and low-temperature manganese and fluorspar veins in the vicinity of the Lightning Dock KGRA.

discovered vents east and south of Rodeo form a link between them and suggest that the Animas Valley eruption may have been derived from a source of regional extent. A northeast-trending line drawn from the southern end of the San Bernardino field to the Animas cone, via the Rodeo centers, is 75 km long. If projected another 30 km it would reach the hot wells of the Lightning Dock KGRA. Deep basaltic magma should be considered as a possible ultimate heat source for the Lightning Dock KGRA (see section on geochemistry below).

Geologic Controls of Lightning Dock Geothermal Anomaly

Background. Chemical analyses of hot water from wells at the Animas geothermal anomaly are shown in Table 9A. The normal temperature of ground water in the Animas Valley is between 17.8 and 18.9°C. Reeder (1957) showed it to be 1.1 to 5.5°C warmer than normal over a wide area on the east side of the Animas Valley. According to Reeder, "chemical analysis of the water...shows it to be sodium sulfate water. The chloride and fluoride contents are higher than for other waters in the valley. The source of this water is not known, but because it contains only about 1,000 ppm of dissolved solids, it probably is chiefly meteoric water... Visible evidence of active volcanism nearby is lacking. The proximity of a recent fault...to the hot wells in sec. 7, T.5S., R.19W., and the similarity in trend of the fault and associated fault zone to the area of abnormally high ground-water temperatures...are further indications of structural control of the hot water area, as are the high fluoride content of the water from wells along the line of high water temperature."

Prior to our work, there were several indications that the Lightning Dock geothermal anomaly might be the surface expression of a major high-enthalpy geothermal system, associated with young rhyolitic volcanism. Unfortunately, these indications have not been confirmed.

Specifically, it seemed possible that rhyolite encountered in the

Table 9a. Chemical analyses, in parts per million, of water from wells in the Animas Valley geothermal anomaly (from Summers, 1965b).

CONSTITUENT	THREE WELLS HIDALGO COUNTY (235.19W.7.23 N)			
	NO. OF ANAL.	MIN.	AVG.	MAX.
Dischg. (gpm)	—	—	—	—
Temp. °F (max. rpt.)	—	—	—	240
SiO ₂	3	135	138	141
Al	1	—	0.1	—
Fe	1	—	0.07	—
Mn	1	—	0.00	—
Pb	—	—	—	—
Cu	—	—	—	—
Zn	—	—	—	—
Ca	4	19	2.2	24
Mg	4	0.7	1.2	1.5
Na	1	—	364	—
K	1	—	21	—
Li	—	—	—	—
Mo	—	—	—	—
As	—	—	—	—
Se	—	—	—	—
HCO ₃	6	145	159	181
CO ₃	6	0	3.3	7
SO ₄	4	459	476	509
Cl	6	78	82	85
F	3	9.9	11.3	13
Br	—	—	—	—
I	—	—	—	—
NO ₃	5	0.2	1.6	6
B	1	—	0.45	—
Total Solids	4	1020	1103	1160
Hardness as CaCO ₃	5	52	5.8	66
Noncarbonate Hardness as CaCO ₃	4	0	0	0
Specific conductance (μmhos/cm)	6	1510	1590	1669
pH	3	7.6	8.1	8.5
Total β-γ activity (μμC/l)	1	—	12	—
Ra (μμC/l)	1	—	0.3	—
U (μg/l)	1	—	0.2	—

discovery well might be part of an active or recently-active dome. In the nearby Pyramid Mountains, Flege (1959) had described rhyolite necks, flows and breccias (North Pyramid rhyolite flows, South Pyramid rhyolite breccia), which he interpreted as having erupted after Basin and Range faulting and tilting. The flows were said to have been funneled down present-day valleys. If true, this would make them late Pliocene or younger. It seemed that Plio-Pleistocene rhyolites might not be confined to the Pyramid Mountains. The map of Ballmann (1960) showed Quaternary rhyolite and dacite domes and flows in the Knight Peak area, some 40 km northeast of the Pyramid Mountains. The U.S. Geological Survey map of New Mexico (Dane and Bachman, 1965) rendered these rocks by the symbol Qv, used elsewhere in the State only for the ring-fracture domes of the Valles caldera.

Widespread hydrothermal alteration in the Pyramid Mountains, the Quaternary basalt cone about 30 km southwest of the hot wells, and Holocene fault scarps in valley fill could have been cited as further evidence for the geological conditions favoring a major geothermal system.

Results of this investigation.

Summary

The results of this study can be summarized as follows:

- (1) There is no evidence for post-Oligocene rhyolitic volcanism in the vicinity of the Lightning Dock KGRA.
- (2) Deep fracturing related to the intersection of an active Basin and Range fault with the ring-fracture zone of the Oligocene Muir cauldron may provide a conduit for thermal waters.
- (3) Hydrothermal alteration occurred in two stages:
 - (a) During collapse of the Muir cauldron in Oligocene time, unrelated to the present thermal anomaly, and

(b) during activity of Miocene or younger hot springs and shallow vein-forming hydrothermal fluids (Figure 19).

(4) Miocene and younger shallow low-temperature veins, and deposits from extinct hot springs, are widespread throughout the Animas Valley. The Lightning Dock geothermal activity may be a relict of this activity.

(5) The Animas Valley and adjacent basins of the Basin and Range province show some of the characteristics of rifts (high heat flow, high seismicity, basaltic volcanism). The ultimate heat source may be deep-seated basalt near the liquidus.

Evidence Against Post-Oligocene Rhyolite

Evidence for youthful rhyolitic activity has proved to be spurious. It has been known for some time that the supposedly Quaternary volcanic rocks of Knight Peak area are, in fact, Oligocene (Elston, 1968). In the Pyramid Mountains, the rhyolite domes and flows around Pyramid Peak, cited by Flege (1959), have been reinterpreted as outer-ring fracture domes of the Muir cauldron. The unconformity beneath them has been interpreted as caused by collapse of the Muir cauldron, not by Basin and Range faulting. The "rhyolite breccia" around South Pyramid Peak has been reinterpreted as ash-flow tuff caldera fill.

Although the rhyolite chips recovered from the McCants wells have not been definitely identified, the mineral assemblages of clasts are similar to assemblages in the Oligocene Pyramid Mountains Volcanic Complex. The rock is unlikely to be modern.

Age of Hydrothermal Alteration

The rocks of the lower part of the Pyramid Mountains Volcanic Complex tend to be strongly altered, especially in Woodhaul Canyon, south of Lightning Dock

Mountain. Alteration has not yet been studied, but has the aspect of fumarolic argillic alteration, common around volcanic centers. Most of it is confined to the tuff of Woodhaul Canyon and older rocks. Alteration seems to have been most intense during the first stage of eruption and collapse of the Muir cauldron, prior to eruption of the tuff of Graham Well. It appears to be unrelated to the modern geothermal anomaly. Locally, a small amount of alteration is associated with the young hydrothermal veins described in the next section.

Hydrothermal Veins and Extinct Hot Springs

The Lightning Dock geothermal anomaly may be a remnant of a hydrothermal system that was once much more widespread. Many hot springs were active in post-20 m.y. time on both sides of the Animas Valley, from the Gila River to at least 50 km south of the U.S.-Mexico border, a distance of about 200 km. The evidence lies in numerous travertine deposits and calcite veins, some of which grade downward or laterally into formerly commercial veins of fluorspar or psilomelane (Figure 19). The mineral deposits have been described elsewhere in some detail (Rothrock and others, 1946; Elston, 1963, 1965; Garcia-Gutierrez and Garcia-Gutierrez, 1969; Elston and others, 1979).

The veins are shallow and geologically young. Throughout the Animas Valley, they generally trend north or northwest, parallel to the major Basin and Range faults. In the Caprock Mountain manganese district, at the northern end of the Animas Valley near the Gila River, veins are partly emplaced in Gila Conglomerate, the Miocene and younger basin fill of this part of the Basin and Range province. The footwall of one of the veins, the Consolation, is a basaltic andesite dated at 20.6 ± 0.5 m.y. (Elston and others, 1973). A nearby vein, the Cliffroy, changes abruptly from opalized psilomelane to travertine, a few meters below the present surface.

Veins in and near the Lightning Dock KGRA: At the Doubtful (or Animas) mine, located at the foot of Lightning Dock Mountain, the fluorite-bearing veins grade laterally into banded calcite. An early generation of gray and white banded, coarse calcite is cut by veins of black manganese-bearing calcite, which in turn has cores of late coarse white calcite. Although the banded calcite is not a true travertine spring deposit, near-surface conditions are suggested by the fluid-inclusion studies described below.

Southeast of the Doubtful mine, north of Woodhaul Canyon, a swarm of calcite veins has been found. Some vein zones are 60 m wide and include veins of solid calcite 12 m wide.

In the northern edge of the map area, in sec. 2, T.24S., R.19W., northwest-trending fluorite-calcite veins cut across northeast- and east-trending copper and silver veins. The fluorite veins probably belong to the Miocene or younger period of mineralization.

Fluid-inclusion studies: Fluid-inclusion studies were made on fluorite crystals from the Pyramid Mountains by T. J. Bornhorst and E. E. Erb, Graduate Research Assistants, under the direction of G. P. Landis. The purpose was to determine temperatures of entrapment of fluids and to find indications of boiling (Table 9B).

The heating stage was built at the University of New Mexico by G. P. Landis and calibrated with organic and pure metal standards. Filling temperatures of inclusions were reproducible to $\pm 2^{\circ}\text{C}$.

Fluid inclusions were measured in fluorites from the Doubtful mine. Some inclusions were 100 percent liquid, others were 100 percent gas, but a gas content of less than 30 volume percent was most common. Apparent temperatures ranged from 137° to greater than 290° in samples from the northern of two

Table 9b. Fluid Inclusion Filling Temperatures

District:	Host Mineral	°C Temp. Range
Animas District:		
Spar Bonanza Mine	calcite	195 $\geq$ 263
Doubtful Mine		
Stills Shaft	grn. fluorite	136 - 290
	clear fluorite	150 > 245
McCabe Shaft	grn. fluorite	147 - 252
	clear fluorite	140 > 349
Pyramid (Lordsburg) District:		
Robert E. Lee Mine	quartz	170 - 241
	white calcite	> 360
Lone Star Prospect	grn. fluorite	172 - 174
	clear fluorite	160 - 165
	white fluorite	150 > 303
Gillespie District:		
Winkler Anticline	lt.grn. fluorite	142 - 178
Fluorspar Prospect	early dk.grn. fluorite	169 - 175
	lt.purple fluorite	178 - 181
	dk.purple fluorite	158 - 173
	olive fluorite	126 - 146
	crystal calcite	153 - 163
	late crystal quartz	206 - 243

shafts and from 147° to greater than 349° in samples from the southern shaft. The wide range of temperatures and the occurrence of several types of primary inclusions suggests that the mineralizing fluid was boiling. The minimum temperatures approach the true temperature of entrapment. They were measured in inclusions with only a small amount of water.

Fluorite from veins in the Pyramid subdistrict yielded a narrow filling temperature range of 160 to 174°C (not corrected for pressure) for primary inclusions. The narrow range of temperatures, and uniformity in the type of inclusions, suggests that the liquid in these veins did not boil.

Summary of evidence relating veins to the geothermal anomaly: There is no proof that the Lightning Dock geothermal anomaly is related to fluorite veins, but several indications suggest that it is possible:

- (1) The veins are geologically young (Miocene or younger).
- (2) The veins are geologically shallow.
- (3) The largest known concentration of veins is exposed in the bedrock nearest to the hot wells. Between the Doubtful mine and the hot wells, piedmont deposits cover all bedrock.
- (4) The thermal waters of the hot wells are anomalously high in fluorine (about 11.4 ppm, Table 9A); the veins carry fluorite.
- (5) Fluid-inclusion studies suggest that the vein-forming fluid was boiling, an indication of near-surface conditions.
- (6) The temperature of formation of fluorite in the Doubtful mine (137 to 147°C) measured by fluid-inclusion studies, was between the surface temperature of water from the McCants wells and the indicated subsurface temperature.

Structural Control

Evidence already cited suggests that hot water rose from depth through fractures created by the intersection of a Basin and Range fault and the ring fractures of the Muir cauldron. It cannot be precluded that another cauldron centered on the Peloncillo Mountains to the west, also influenced structural control.

Characteristics of Animas Valley

Geothermal anomalies are common in areas of active volcanism and active seismicity. While no evidence has been found for recently-active silicic volcanism, the possibility of an extensive basaltic heat source has already been raised.

Fault scarps in Quaternary valley fill on both sides of the Animas Valley are evidence for seismic activity. The largest earthquake ever recorded in the western mountain region of North America occurred on May 3, 1887 (Modified Mercalli Intensity VIII to IX) near Baviste, Sonora, lat. 31°N. , long. 109°W. , about 30 km south of the common junction of New Mexico, Arizona and Sonora (Coffman and von Hake, 1973).

Conclusions

Summary. The Lightning* Dock KGRA includes parts of the Pyramid Mountains and parts of the Animas Valley. If the conclusions of this report are correct, geothermal hot water or steam are most likely to be developed in the valley part. Deeply convecting heated meteoric water evidently rose through a zone of permeability created by the intersection of the Animas fault and the ring-fracture zone of the Muir cauldron. The volcanic bedrock of the area is relatively impermeable and the surficial capping of piedmont deposits is only a

few tens of meters thick. Hot water rising through fractured ground could come close to the surface, with subsequent minor dilution by cold groundwater. The area considered favorable for future discoveries of hot water by this interpretation is shown in Figure 17. In general, deep hydrologic conditions in the Animas Valley are unknown.

There are no indications from wells or surface geology that geothermal waters exist beneath the mountain part of the Lightning Dock KGRA. Hydrothermal alteration is prominent in the Pyramid Mountains, but is more likely to have occurred during activity of the Muir cauldron in Oligocene time than during the present episode of hydrothermal activity. An Oligocene cauldron complex may provide structures that control present-day water circulation but is unlikely to be a modern heat source.

Hot water has been reported from the Playas Valley, east of the Pyramid Mountains. According to Mr. Rex Kipp (personnal communication, July 21, 1975), hot water was found in a well on the Muir (Kipp) Ranch, in NE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 10, T.23S., R.17W. A 12-inch irrigation well on the Cooke farm near Lordsburg was also said to have yielded anomalously warm water (about 50°C at 365 m).

Regional Prospects. Control of geothermal water by the intersection of a Basin and Range fault zone and a mid-Tertiary cauldron complex is not unique to the Lightning Dock KGRA. A similar case can be made for almost every other major geothermal anomaly in the southwestern corner of New Mexico. For example, Mimbres Hot Springs is at the intersection of the Mimbres Hot Springs fault and the inner caldera wall of the Emory cauldron (Elston and others, 1975). Faywood Hot Springs lies on the northeastern margin of the Mangas Trench and directly next to an outer ring-fracture dome of the Emory cauldron. Lower Frisco Springs can be interpreted as localized by the intersection of the southwestern margin of the Mangas Trench with the outer ring-fracture zone of the Bursum cauldron.

The age, position and existence of the Gila Cliff Dwellings cauldron are controversial, but Ratte and Gaskill (1975) and Elston and others (1976) both show Gila Hot Springs to be near the intersection of a Basin and Range fault zone (the northern side of the Gila Hot Springs Graben of Ratte and Gaskill, 1975) and the inferred margin of the Gila Cliff Dwellings cauldron (or caldera).

If these relationships are more than a coincidence, areas south of the Lightning Dock. KGRA hold favorable prospects for future discoveries of geothermal hot water or steam. Deal and others (1978) indicate a number of cauldrons in southwestern New Mexico. Several of these cauldrons are larger than the Muir cauldron. Evidence for seismicity and volcanism in the recent geologic past becomes more impressive as one approaches the junction of New Mexico, Arizona and Sonora.

GEOCHEMISTRY

Water Geochemistry

Reconnaissance studies of the chemistry of 55 thermal and non-thermal waters of the Animas Valley are compiled in Appendix 6 and summarized in Figures 20 and 21, along with the geology and well locations (Figure 22).

Reservoir temperature estimates were calculated using chemical methods described in Landis and Logsdon (1980). A comparison of temperatures calculated by various methods is given in Table 10. The last column lists a 'Best Estimate' reservoir temperature which is a subjective appraisal of 'reasonable' average or interpreted temperature. The data from analyses near Lightning Dock are plotted and contoured in Figure 23. Best estimate chemical temperatures for other samples in the Animas Valley appear in Figure 24.

ANIMAS VALLEY

Figure 20. Silica geothermatures in the Lightning Dock KGRA region. See also Fig. 2.

Figure 21. Na-K-Ca geothermatures in the Lightning Dock KGRA region. See also Fig. 3.

Figure 22a. Locations of the P-series and LD-series water samples in the Animas and adjacent Lordsburg and Playas valleys. Box shows location of Figure 22b.

Figure 22b. Locations of P-series (•) and An-series (+) water samples in the lower Animas Valley. Samples P2, P3 and P4 are from the hot wells.

Figure 22c. Generalized structural setting of the lower Animas Valley. Ball and bar are on the downthrown side of high-angle faults. The hot wells are located near the intersection of the ring-fracture margin and the Animas Valley fault (see Appendix 3). The eastward-dipping high-angle fault along the flank of the Peloncillo Mountains is reported by S.G. Wells (personal communication, 1980).

Table 10. Comparison of Calculated Reservoir Temperatures ($^{\circ}\text{C}$)

Sample	Na - K	Na-K-Ca	Na-K-Ca	Alpha Quartz (BARS)			Alpha	Chalced.	Best	
		[F&T]	[UNM]	L-V	500	1500	2000	Cristoba.	Estimate	
<u>P-series:</u>										
P 1	109	38	32	80	71	59	53	38	59	38
P 2	169	174	169	168	152	128	118	110	137	169
P 3	164	170	165	165	150	126	116	108	135	165
P 4	153	160	156	150	136	114	105	95	122	153
P 5	129	60	53	94	84	69	63	48	70	50
P 10	85	71	65	112	100	83	76	63	87	64
P 13	112	49	43	123	111	92	84	72	97	97
P 14	128	38	32	100	90	74	68	53	76	76
P 15	129	58	51	85	75	62	56	41	62	60
P 20	101	39	32	102	92	76	69	55	78	78
P 22	102	42	35	95	85	70	64	49	71	71
P 23	73	46	39	77	69	56	51	36	56	38
P 24	152	157	154	169	153	129	118	111	128	142
P 25	137	50	43	85	75	62	56	41	62	56
<u>An-series:</u>										
An 1	126	39	32	110	98	82	74	62	85	62
An 2	85	58	52	53	47	39	35	17	35	52
An 3	131	41	34	119	107	89	81	69	93	69
An 4	130	94	87	140	126	105	96	86	112	86
An 5	139	60	53	102	92	76	69	55	78	54
An 6	132	52	46	78	70	57	52	36	57	54
An 7	117	52	46	78	69	57	51	36	56	54
An 8	133	41	34	83	74	61	56	40	61	40
An 9	117	61	54	---	---	---	---	---	---	55
An 10	116	58	51	89	78	65	59	44	66	62
An 11	129	45	38	96	86	71	65	50	72	47
An 12	122	45	38	97	87	72	66	50	73	47
An 13	127	64	57	81	72	59	54	39	59	58
An 14	119	45	38	96	86	71	65	49	72	47
An 15	131	44	37	78	70	57	52	37	57	37
An 16	114	48	41	88	78	64	59	44	65	46
An 17	150	81	73	78	70	57	52	36	57	80
An 18	130	45	38	89	78	65	59	44	66	45
An 19	125	30	23	91	81	67	62	46	68	60
An 20	128	39	32	101	91	75	69	54	77	70
An 21	141	49	42	89	78	65	59	44	66	60
An 22	103	48	41	82	73	60	55	39	60	55
An 23	127	42	35	88	78	64	59	44	65	43
<u>LD-series:</u>										
LD 1	133	143	139	83	74	61	56	40	61	87
LD 2	150	151	100	91	81	67	61	46	68	95
LD 3	199	62	54	95	85	70	64	49	71	52
LD 4	58	58	52	82	72	60	54	39	60	58
LD 5	100	95	88	99	89	73	67	52	75	93
LD 6	171	36	29	89	79	65	60	45	56	45
LD 7	220	21	14	99	89	74	67	53	75	53
LD 8	154	19	12	97	87	72	66	50	73	50
LD 9	---	45	36	99	98	74	67	53	75	45
LD 10	---	58	49	91	81	67	61	46	67	48
LD 11	225	70	62	104	93	77	71	58	80	60
LD 12	289	50	42	86	76	63	58	42	64	42
LD 13	250	56	49	91	81	67	61	46	67	48

Figure 23. Isopleths drawn for best estimate shallow reservoir temperatures of P-series (*) and An-series (+) waters. Values are calculated from the water chemistry and listed in Table 10.

Figure 24. Best estimate shallow reservoir temperatures for other areas in the Animas Valley based on water chemistry; values are listed in Table 10.

Figure 25. Temperatures contours based on alpha quartz-controlled silica solubility near Lightning Dock, KGRA (from Landis and Logsdon, 1980).

In Figure 23 the hot wells define a recognized hot spot from which the chemical temperatures indicate a northerly thermal dispersion similar to that originally described by Kintzinger (1956) from his temperature and gradient survey. Of interest is the apparent thermal ridge and continued "high temperature" water to the south and west of the hot wells. The same general features are recognized in the temperature contours based upon alpha quartz-controlled silica solubility (Figure 25).

Oxygen Isotope Geochemistry of Lightning Dock KGRA

Results of the Lightning Dock oxygen isotope study are presented in Table 7. All groundwater samples are from relatively shallow (<40 m) wells. Since samples LD 1 - LD 5 are from the Lordsburg and Playas Valleys, not the Animas Valley, they will not be considered in this discussion.

The $\delta^{18}\text{O}$ values of groundwaters from the KGRA and adjacent parts of the lower Animas Valley range from -8.9 permil to -10.5 permil. Groundwaters from the upper Animas Valley range from -8.1 permil to -10.1 permil. Summer rainwater has an isotopic value near -5 permil. Interpretation of these data is complex and requires some knowledge of the hydrology of the valley and the meteorology of southwestern New Mexico, as well as the geology of the region.

Preliminary hydrogen isotope studies of the Animas Valley, conducted separately from this study, show clearly that all the groundwaters of the Animas Valley are meteoric in origin (M. J. Logsdon, personal communication, 1980). However, it is clear from the oxygen isotopes that, while a large percentage of the precipitation in the Animas Valley falls during the summer rains, the groundwaters do not represent samples of the present-day summer rains. This paradox is not difficult to resolve. Summer rainstorms are apt to be of high intensity but short duration. Rain which falls on the valley floor

is unlikely to add significantly to recharge, because the valley floor is an area of net discharge due to high rates of evapotranspiration and low rates of infiltration associated with the presence of caliche in the soil. A significant portion of the rain which falls on the steeper terrain of the recharge areas in the mountains will be lost as surface runoff during high intensity storms. Therefore, a relatively small component of the annual meteoric water recharge will be provided by the summer rains sampled in this study. The principal source of meteoric water recharge in the Animas Valley is believed to be winter precipitation which falls in the surrounding mountains. Such precipitation should have considerably more negative $\delta^{18}\text{O}$ values than the summer rains (Dansgaard, 1964), and proportionally more of the precipitation should infiltrate to the water table because of lower evaporation rates. This hypothesis is supported by a detailed isotope study of a similar valley in southern Arizona (Simpson and others, 1972). Therefore, the effective modern meteoric water has a $\delta^{18}\text{O}$ value near -9.5 permil, which is in good agreement with the regional study of Taylor (1974).

The waters of the lower Animas Valley are generally under saturated water table conditions, although locally perched conditions are encountered due to clay lenses in the playa deposits of Pleistocene Lake Animas. Most of the upper valley has both perched and saturated water table conditions (Reeder, 1957). Groundwater samples which have $\delta^{18}\text{O}$ values near -9.5 permil represent samples from shallow aquifers recharged by modern meteoric water. Values which are significantly more positive than -9.5 permil probably represent modern meteoric water which has undergone evaporation during infiltration or perhaps due to capillary action above a shallow, perched water table.

Waters which have $\delta^{18}\text{O}$ values significantly more negative than -9.5 permil represent more complex and problematical histories. Analysis of the chemical,

isotopic and temperature data indicates that there is a statistically significant negative correlation between $\delta^{18}\text{O}$ values and temperature, concentration of chlorine, and concentration of boron (Landis and Logsdon, 1980). The deeper, high temperature reservoir water is more depleted in ^{18}O than the shallow aquifer water. This is a surprising result, since higher temperatures should favor increased ^{18}O exchange with the enclosing rock and therefore, a shift to more positive $\delta^{18}\text{O}$ values. The more negative $\delta^{18}\text{O}$ water required by the data may be "old" Pleistocene water within the deep gravels of the Animas Valley basin, or it may represent a recondensed vapor phase on the distal edge of a boiling geothermal system at depth. The low salinities of the Lightning Dock waters favor the boiling hypothesis, but the "old, cold" water hypothesis cannot be excluded. Deep circulation times for many geothermal systems are estimated at >30,000 years (e.g. Craig, 1963). For a steady-state model of the Animas Valley, given known rates of recharge, the residence time for basin waters is 5,000 to 50,000 years. Therefore, a Pleistocene water of some "light" isotopic composition is probable.

Spatial analysis of the oxygen isotope data (Figure 26) provides some information on the subsurface flow of fluids in the Lightning Dock area. The relatively negative values of $\delta^{18}\text{O}$ north of the hot wells represents the dispersion of deep, hot water in the regional groundwater flow. The southwest trend suggested by the contoured data is believed to represent the trace of a deep structure, probably a fault, along which reservoir fluids are leaking into shallower aquifers. The negative $\delta^{18}\text{O}$ values of the deep water component indicate that the geothermal waters have not interacted with the Paleozoic marine carbonates which underlie the Pyramid Mountain volcanics in the Animas Valley.

Figure 26. Isopleths drawn for $\delta^{18}\text{O}$ values of P-series sample waters.

GEOPHYSICS

Electrical and Gravity Studies

Introduction. Lightning Dock KGRA (Figure 14) has been considered a prime geothermal prospect since boiling water was encountered near the ground surface in 1948. The discovery led, several years later, to what is considered the first instrumental geothermal survey made in New Mexico, a shallow (1 to 2 m deep) temperature survey by Kintzinger (1956). Kintzinger's results (Figure 27) mapped a fan-shaped anomaly over the hot wells, spreading to the north. This pattern may be explained by the groundwater flow direction which was essentially north to south then (Reeder, 1957) but more recently appears to have swung more to the west or northwest (Summers, 1976). Figure 27 also locates the two electric bipole sources, each about 2-km long, which were used in our initial resistivity reconnaissance of the area.

Various artificial and natural source electrical methods (Table 8) have been applied in the evaluation of this area, beginning with bipole-dipole surveys run in 1975 (Figure 28). This reconnaissance work covered an area of more than 125 km². A combined asymmetric Schlumberger and bipole-dipole equatorial sounding was included in this phase of the program, followed by a dipole-dipole line 8-km long using 500 m dipoles (Figure 28). A limited 4-km long self-potential traverse was also completed in 1975. In 1976, the telluric profiling method was applied over the hot wells and a deeper probing magnetotelluric profile was made using the five stations shown in Figure 28. Finally in 1977, a downhole-remote (D-R) mapping survey was carried out using one of the hot wells (Figure 28) in an attempt to better determine the areal extent of the near-surface geothermal occurrence. Various stages of the Lightning Dock KGRA electrical evaluation program have been reported during the

Figure 27. One-meter temperature map of the Lightning Dock study area (after Kintzinger, 1956).

Figure 28. Location of electrical studies in the Lightning Dock area.

course of the study by Jiracek and others (1975), Jiracek and Smith (1976), Jiracek and others (1977), Smith and others (1977) and Smith (1977 and Appendix 2). Further results of the downhole-remote survey were presented by Jiracek and Gerety (1978).

Figure 28 locates the KGRA boundaries and the Animas Valley, which is bounded by the Peloncillo Mountains and the Pyramid Mountains to the west and east, respectively. The approximate location of outer ring fracture zone of the Muir cauldron is indicated in Figure 28. Oligocene volcanism is not the source of the present geothermal anomaly, but the projected intersection of the ring fracture with a late Pleistocene - early Holocene fault scarp (Figure 28) described by Reeder (1957) suggests the structural control for the anomaly.

Gravity studies. Results of the regional gravity survey of the area have been presented by Preslar (1976) and discussed by Jiracek and others (1977) and Smith (1977). The complete Bouguer anomaly results are mapped in Figure 29. The steep gravity gradients on the eastern and western margins of the valley north of the hot wells reflect the high-angle normal faults that form the Animas graben. On the western side of the valley a fault or system of faults trends north, creating a gravity signature typical of the Basin and Range province. On the eastern margin of the figure the gravity contour lines deflect from a north-south trend to a northeast-southwest trend in the vicinity of the hot wells.

Given a reasonable range of density contrasts ($0.3-0.4 \text{ g/cm}^3$) and the extremes of the gravity data (20-40 mGal), estimates of the center thickness of the valley fill range from 1.2 to 3.6 km. Immediately south of the hot wells, the gravity displays a significant residual anomaly ($\sim 5 \text{ mGal}$) which undoubtedly correlates with a shallow ridge-like feature observed on all electrical

Figure 29. Complete Bouguer anomaly gravity map of Lightning Dock study area (after Preslar, 1976).

surveys. This, as well as the large positive anomaly southeast of Cotton City, could be due to buried ring-fracture domes, since they are directly in line with the extended cauldron boundary (Figure 28).

Electrical studies.

Direct Current Mapping

Figures 30 and 31 present total field apparent resistivity contours derived from the two bipole sources indicated. The regions of highest apparent resistivity (20-60 ohm-m) at the eastern and western margins of the figures are due to the proximity of more resistive rocks. On the western edge, the Peloncillo Mountains are composed of a sequence of Precambrian granite, Paleozoic through Cretaceous sedimentary rocks, and Tertiary intrusions. To the east, the Pyramid Mountains are mainly formed by the rhyolitic ash-flow tuffs of the Muir caldron, with isolated exposures of Paleozoic and Cenozoic sedimentary rocks and Cretaceous and Tertiary basalt and andesite.

In both Figures 30 and 31, the observed patterns are complex, but both reveal a significant high resistivity anomaly passing near the hot wells. This irregular high resistivity ridge extends from east of Cotton City through the hot wells to the northeastern corner of the figures. The feature is observed with both bipole orientations; therefore, it points to a real structure in the subsurface. A comparison with the probable extension of the ring-fracture zone of the Muir caldron (Figure 28) and the deflected gravity gradient and residual anomaly in Figure 29 suggests that the ridge may be produced by resistive volcanic domes within the buried ring-fracture zone of the caldera.

The decrease in resistivity toward the center of the valley, in the vicinity of Valley View Church and to the north, is probably due to increasing thickness of water-saturated sedimentary strata and increasing salinity of the

Figure 31. Total field apparent resistivity map of Lightning Dock study area derived from east-west bipole transmitter.

waters. These conclusions are supported by gravity data (Figure 29) and by the northwesterly flow of groundwater at the hot wells.

An isolated, closed, low resistivity contour is associated with the hot wells in both Figures 30 and 31. Such a pattern is expected where there is a near-surface conductive anomaly like the boiling, slightly saline water encountered by the wells. The geometry and location of these closures relate to the bipole source orientations and in either case indicate that the thermal waters are rising within a constricted zone or conduit at depth. This conduit could possibly be a flexure in Basin and Range faults caused by deflection at the caldera margin.

Southeast of the hot wells, in both figures, there is another low resistivity region separated from the lows in the center of the valley and near the hot wells by the high resistivity ridge. This may reflect a zone of groundwater accumulation in sedimentary fill within the Muir cauldron.

Results of the downhole-surface radial field survey presented in Figure 32 detail the region surrounding the hot wells. The survey was run in a fashion identical to that described later in the Las Aluras Estates discussion. The patterns mapped in Figure 32 are explained by the same features seen in less detail by the bipole-dipole surveys of Figures 30 and 31. The NNE-SSW trending high resistivity ridge, to the east of the hot wells, is shown by the 18 and 22 ohm-m closures. Low resistivity is evident to the east of the ridge and separately encloses the hot wells in a near-circular fashion. The extension of low resistivity from the central anomaly to the northwest is along the groundwater flow direction (Summers, 1976).

Figure 32. Downhole-remote radial field apparent resistivity map at Lightning Dock KGRA.

Direct Current Soundings

A combined asymmetric Schlumberger and bipole-dipole equatorial sounding was conducted on the E-W bipole transmitter (Figure 31) and to the north perpendicular to it (Figure 31). The upper three layers are interpreted to indicate progressively more saline groundwater with depth in the valley fill lying above a relatively impermeable one (27 ohm-m). This zone is geologically interpreted as identical to the volcanic rocks encountered between 576 m and 1766 m at a nearby oil test well, the Cockrell Corp., No. 1 Federal-Pyramid located at T.24S., R.19W., Sec. 31.230 (Summers, 1976). Moreover, this is likely the same welded rhyolitic tuff found at a shallow depth (~25m) at the hot wells (Kintzinger, 1956). Rhyolite chips recovered from drilling in the vicinity of the hot wells are similar in rock type to the rhyolite domes and flows in the Pyramid Mountains. The most resistive layer, sounded below 2288 m in Figure 33 (104 ohm-m), correlates with the Paleozoic (1766 m depth) and Precambrian rocks (2177 m depth) reported by the oil test well log (Summers, 1976).

Results of the dipole-dipole line (Figure 28) crossing the hot wells and sounding to N=14 using 500 m dipoles are given in Figure 34. Modeling of the observed pseudo-section used the program published by Dey and Morrison (1977). The calculated results in Figure 34 are the final update of the preliminary results produced by C. M. Swift, Jr. (personal communications, 1976), which were reported on by Smith (1977) and Jiracek and others (1977).

The most prominent feature in Figure 34 is the resistive ridge which has been reduced from a preliminary true resistivity of 50 ohm-m to 30 ohm-m. This now agrees with the results and discussion of Figure 33. A value of 30 ohm-m still seems low for the rhyolitic tuff represented by this ridge, but an even further reduction was necessary to match the observed dipole-dipole results

Figure 33. Preliminary results of combined asymmetric Schlumberger and equatorial bipole-dipole sounding at Lightning Dock KGRA.

Figure 34. Dipole-dipole pseudosection sounding at Lightning Dock KGRA and two-dimensional model calculations.

(Figure 34). This was accomplished by extending the 4 ohm-m surficial zone beneath the hot wells, to depth in a conduit-like fashion. Such a model is certainly not unique; however, the two-dimensional representation in Figure 34 can be thought of as lending support to the hypothesis that geothermal waters are migrating up a permeable zone in a rhyolitic ridge and spilling over on the west. Elimination of the 4 ohm-m "conduit" from the model in Figure 34 increases the calculated peak resistivity value from 32 to 44 ohm-m. The 1-4 ohm-m zones on the eastern and western ends of the dipole-dipole survey, and mapped in Figures 30, 31 and 32, do not appear to be connected to the thermal aquifer. They are probably clay-rich, saline-water zones and are responsible for the low apparent resistivities observed at spacings of $N=12-14$ in Figure 34. This suggestion was advanced by Jiracek and Smith (1976) who also considered the possibility of a low resistivity region at depth to explain these results.

Telluric and Self-potential Profiling

Very limited telluric and self-potential surveys were run over the hot wells in the Animas Valley beginning from roughly Road Well on the east and traversing beyond the hot wells (Figure 35). The self-potential survey was accomplished using a single reference electrode emplaced at Road Well, and repeatable readings were made on three consecutive days. The telluric survey using ~ 300 m dipoles definitely shows the effect of the high resistivity ridge centered to the east of the hot wells, and there appears to be a negative SP anomaly of about 10 mV associated with the hot water zone (Figure 35). These results are compared in Figure 35 to the corresponding gravity profile and a segment of the total field mapping results from the E-W bipole transmitter (Figure 31).

Figure 35. Comparison of gravity, apparent resistivity, relative telluric field strength, and self-potential profiles across hot wells at Lightning Dock KGRA.

Magnetotelluric Soundings

Magnetotelluric soundings (Figure 28) in the Animas Valley were made in cooperation with Geonometrics, Inc., Berkeley, California. The University of New Mexico cryogenic magnetometer sensor was used with the four channel analog recording system operated by Geonometrics in 1976. Data were recorded over a period range of 0.1 to 100 seconds in two bands. Processing of the data was carried out in the standard fashion similar to that described below in the COCORP studies; however, the vertical magnetic field was not recorded. As an example of the results, we have presented a pseudosection of the apparent resistivity versus period data for the $\sim$ E-W principle direction in Figure 36. This direction would correspond to the transverse magnetic (TM) mode or the dip direction, since Basin and Range structure is predominately north-south. The TM mode results in greater change in apparent resistivity across a lateral discontinuity such as is clearly evident on the west side of the traverse (Figure 36). This reflects the sensing of the upthrown resistive block of the Peloncillo Mountains to the west; surprisingly the Pyramid Mountains to the east have not affected the results to any noticeable degree. The results to the east are dominated by a high resistivity closure ($\sim$ 30 ohm-m) reflecting the high resistivity rhyolitic ridge. Perhaps from a geothermal standpoint, however, the most important aspect of the results may be a conductive zone ($\sim$ 5 ohm-m) lying below the ridge in the section (Figure 36). Preliminary one-dimensional modeling places this conductor at a depth of about 7 km. This may represent the ultimate source of the Animas Valley thermal anomaly, possibly a basaltic magma body in the shallow crust. The nearest eruption of Pleistocene basalt is only 30 km southwest of the hot wells in T.28S., R.20W.,

LIGHTNING DOCK KGRA - MT PSEUDOSECTION (E ~ EW, ρ_0 IN OHM-M)

Figure 36. Magnetotelluric apparent resistivity pseudosection using approximate east-west electric field (TM) polarization at Lightning Dock KGRA.

Sec. 15.200. The northeast-trending line of basaltic centers that extend from the San Bernardino field of southeastern Arizona into the Animas Valley, a distance of 75 km, was noted previously.

The suggestion that a conductive body is present beneath the resistive ridge under the hot wells is based on a simple one-dimensional interpretation.

We must also consider the possibility that this conductive portion of the pseudosection is related to lateral conductive variations at about the same distance (5-10 km). Very shallow conductive regions are clearly present at such distances as is evident by the bipole-dipole and dipole-dipole results (Figures 30, 31 and 32). Therefore, we must reserve our final interpretation of the MT data until after we have completed two-dimensional modeling.

Conclusions. A conductive zone detected by magnetotelluric soundings may reflect a shallow crustal magma heat source for the Animas Valley thermal anomaly. A more definitive conclusion must await two-dimensional modeling, since lateral conductive zones, present in the valley, may explain the long period magnetotelluric data. However Quaternary basalt has erupted only 30 km to the southwest along a clearly defined structural trend; a crustal magma heat source would give a shallow circulation depth necessary to explain the well-water chemistry.

The occurrence of the Animas Valley thermal anomaly appears to be controlled by the intersection of visible Basin and Range faulting and an older, Oligocene, cauldron ring-feature zone. This is substantiated by the recent detailed geologic mapping and the combined geophysical data. The observed electrical resistivity patterns are consistent with a localized heat flow anomaly exceeding 800 mWm^{-2} (20 HFU) (Lange, 1977; Dellechiaie, 1977). All results point to a conduit-like ascension of thermal waters, controlled by fault intersections, which are dispersed northwesterly by shallow groundwater flow.

Given the diversity of information available for the Lightning Dock KGRA, we may estimate the heat content in the shallow reservoir. This proceeds as follows:

- 1) Volume. Estimated $\sim$ E-W extent of 1.5 km is based on conductive anomaly measured by bipole-dipole, dipole-dipole, telluric and downhole-remote electrical results; estimated $\sim$ N-S extent of 2.5 km is based primarily on downhole-remote mapping; drilling results place the top of the aquifer at about 25 m, and we estimate the average bottom depth to be $\sim$ 200 m based on dipole-dipole soundings. The volume of this shallow subsurface reservoir would thus equal 0.66 km^3 . The discussion of the dipole-dipole results, Figure 34, included a justification for modeling a conduit-like extension of the near-surface conductive zone. Estimation of the volume of this extension is slightly over 0.1 km^3 . This assumed reservoir extension is truncated at 1.5 km depth, which is about the limit of our dipole-dipole resolution (Figure 34). An overall estimate of 0.75 km^3 for the volume of the Lightning Dock KGRA reservoir is considered conservative, since the high heat flow pattern is reported to extend 3 km in length (Dellechiaie, 1977) or possibly as much as 10 km (Lange, 1977).
- 2) Volumetric specific heat. Porosity of the geothermal zone is estimated at 20-25 percent; this value is less than that estimated at Las Alturas Estates owing to a probable reduction in porosity caused by mineral precipitation from the cooling thermal waters. The volumetric specific heat would thus range from 0.65 to $0.70 \text{ cal/cm}^3 \text{ } ^\circ\text{C}$. The porosity estimate is not in agreement with a simple Archie's law calculation using the known water resistivity of 6.3 ohm-m; the bulk

resistivity of the aquifer of 4 ohm-m calculated from dipole-dipole modeling is assumed to reflect a high clay component.

- 3) Reservoir temperature above mean annual. Our data on average reservoir temperature are incomplete. AMAX Exploration, Inc. has occupied at least 31 heat flow holes averaging less than 70 m depth. Some "very high gradients at shallow depths" were observed that became isothermal at depth (Dellechiaie, 1977). High near-surface gradients with a maximum bottomhole (25m) temperature of 102°C have also been reported by Summers (1976). As a working number we have simply chosen 100°C as representative of the entire reservoir and 17°C as the mean annual temperature.

- 4) Approximate heat content calculation,

Heat content $\pm 0.8 \times 10^{15} \times 0.7$ (100-17) cal

Heat content $\approx 5 \times 10^{16}$ cal

$[(2.1 \times 10^{17} \text{ joule}; 2.0 \times 10^{14} \text{ Btu})]$

in the shallow reservoir at Lightning Dock KGRA.

CONCLUSIONS

The Lightning Dock area includes parts of the Pyramid Mountains and Animas Valley. Geothermal waters are most likely confined to the valley part. The waters of the Lightning Dock KGRA hot wells are mixed waters containing about 25 percent deep geothermal fluid at approximately 250°C (Logsdon, 1981). Although no thermal manifestation of the deep geothermal reservoir other than the hot wells is known, significant indications of structurally-controlled seepage of chemically distinct reservoir water into the shallow aquifer define a linear trend southwest of the hot wells. The deep water moves up and along a

major northeast-trending fault or fault system from a reservoir located southwest of the hot wells, mixing with shallow, cold aquifer waters where this northeasterly trending structure intersects the Animas fault and ring-fracture zone of the Muir Cauldron. The heat source for the reservoir is probably Quaternary basaltic magma.

According to Logsdon (1981), the chemistry of the waters of the Animas Valley is produced by a variety of processes, including evaporation and boiling, water rock interactions at high temperature, and mixing of solutions, including low-temperature groundwaters which have been modified by the dissolution of playa evaporites. The calculated reservoir chemistry suggests that the alteration phases associated with the high-temperature waters should include magnesian calcite, Na- and Mg-montmorillinite, illite, Ca-zeolite, chlorite, alkali feldspar, quartz, chalcedony, anhydrite, fluorite, and iron oxides and sulfides (Logsdon, 1981).

The volume of the shallow reservoir is estimated to be at least 0.75 km^3 , with a total heat content of 2.1×10^{17} joules. Higher temperature water is deeper reservoirs to the southwest may also be present; deep drilling and additional geophysical studies will be required to delineate the deep resource.

Las Cruces Area

INTRODUCTION

Setting, Scope and Previous Work

Two areas near Las Cruces, New Mexico were chosen to be the first study areas of geothermal phenomena in the Rio Grande rift: Radium Springs KGRA and Las Alturas Estates (Figure 37). The hot springs at Radium Springs had been used by the Apaches for centuries and are still noted for their curative powers. Presently, they support a health spa, hotel and restaurant. The hot water at Las Alturas Estates, on the other hand, is a recent discovery (Summers, 1976). Several domestic water wells have been drilled since 1967 in a subdivision 5 km southeast of Las Cruces (Figure 38). Their proximity to Las Cruces offered the incentive to evaluate these target areas. Radium Springs is 25 km north of the civic center; Las Alturas Estates is less than 4 km southeast of New Mexico State University.

Chemical analyses of the waters of both Radium Springs and Las Alturas Estates indicate rock-water equilibrium temperatures in excess of 200°C (Table 11). A geothermal reservoir at either area might be an energy resource for electrical power generation or space heating and cooling. Resistivity surveys were designed to delineate the near-surface occurrences of hot water and, if possible, to detect the deepseated structures that govern them.

There was little available literature to guide the initial geothermal investigation at Radium Springs KGRA. The only references to the area were contained in two hydrologic reports (Conover, 1954; King and others, 1971) and one geochemical study (Swanberg, 1975). After the field work at Radium Springs KGRA was completed, a geologic map of the area and several pertinent articles

Figure 37. Radium Springs and Las Alturas Estates study areas.

Figure 38. Las Alturas Estates study area (after Smith, 1977).

Table 11

Selected geochemical geothermometers of ground water in the Las Cruces area, New Mexico

Radium Springs 21.1.10.213

Geothermometer	Estimated temperature	Reference
Na-K-Ca	> 200°	Swanberg, 1975a
Na-K-Ca	169°C	Renner and others, 1975
SiO ₂	100-150°C	Swanberg, 1975a
SiO ₂	156°C	Renner and others, 1975

Las Alturas Estates 23.3.34.200

Na-K-Ca	100-150°C	Swanberg, 1975a
SiO ₂	100-150°C	Swanberg, 1975a

(from Smith, 1977)

were published by W. R. Seager and associates at New Mexico State University (e.g., Seager, 1975a, b). The New Mexico Geological Society also published its 26th guidebook (Seager and others, 1975b), an invaluable reference.

Radium Springs is located at the northern end of the Mesilla Valley and the Mesilla basin, one of the southernmost grabens that comprise the Rio Grande rift. According to Seager (1975b):

The present topography is dominated by intrarift uplifts and basins of late Cenozoic age, but these are superimposed upon a variety of older, very different tectonic features of middle Tertiary and Laramide age.

Seager's discussions of these older features suggest that a Laramide anticline of Paleozoic sediments may be a reservoir for the hot water at Radium Springs. The depth to such a reservoir may be greater than a few kilometers.

Resistivity studies apparently detected a 50-m thick aquifer of thermal fluid at a depth of 120 m throughout the northern end of the Mesilla basin. They also revealed that the hot springs at Radium Springs are not hydraulically connected with the Jornada del Muerto, 4 km to the northwest.

Las Alturas Estates is a suburb of Las Cruces with privately owned and constructed lots and homes. The subdivision cooperative and several individual land owners have drilled domestic water wells that produce warm, mineralized water from depths of less than 120 m. The shallow geothermal anomaly has been encountered only in sec. 34, T.23S., R.2E. This section lies near the eastern edge of the central Mesilla basin, on the piedmont slope above the Mesilla Valley.

Only the reconnaissance geologic map of Kottowski (1960) contains any geologic information about the Las Alturas Estates area. This map is of some help in the interpretation of the resistivity data. The hydrologic report of King and others (1971) mentions the hot wells only in passing.

Resistivity data suggest that the hot water is contained in at least 100 m and perhaps as much as 200 m of sediments of the Santa Fe Group. This aquifer may extend beyond the survey area, south of the hot wells. The aquifer does not appear to extend more than 2 km east, north and west of the hot wells. The depth to the aquifer may be only 100 to 150 m.

Geochemistry and Gravimetry

The work of Swanberg (1975) on the silica and Na-K-Ca geochemical thermometers shows temperatures in excess of 200°C at Radium Springs and in excess of 100°C at Las Alturas Estates (Table 11). Swanberg (1975) looked for but found no high temperature water in the southern Jornada del Muerto. The two occurrences of geochemical temperature anomalies, Radium Springs and Las Alturas Estates, are more than 35 km apart. No temperatures above 100°C were reported between them.

A straight line connecting Radium Springs and Las Alturas Estates parallels a fault inferred from gravity data which bounds the Mesilla basin on the east. Swanberg (1975) called this fault the "Valley Fault". The coincidence of the two temperature anomalies and the 'Valley Fault' prompted him to suggest that "the Valley Fault acts as a conduit for the ascending geothermal fluids" at both Radium Springs and Las Alturas Estates.

Geologic, hydrologic and geophysical evidence do not corroborate this suggestion. Geologic mapping by Seager and others (1976) suggested that Radium Springs does not lie on the "Valley Fault". Las Alturas Estates may not lie on the fault as well. The regional gravity data of Ramberg and Smithson (1975) do not clearly show the "Valley Fault" to pass through Las Alturas Estates. A more detailed gravity map of the Las Alturas Estates area does not show steep gravity gradients that would indicate a major fault near the hot wells (Figure

39). Three to five kilometers west of the hot wells, west of the study area, the detailed gravity data do possess steep gradients (not shown on Figure 39). The major fault bounding the Mesilla basin is west of the water temperature anomaly at Las Alturas Estates. King and others (1971) show the water table at the hot wells to dip southwest, towards the inferred location of the fault. If the "Valley Fault" were a conduit for thermal water near Las Alturas Estates, water rising there would flow away from the hot wells.

Faults that parallel the "Valley Fault" and that displace impermeable rock possibly could act as conduits for the hot water. King and others (1971) suggested that "a fault zone bounding the Tortugas Mountain block" may be largely responsible for the hot water at Las Alturas Estates. Their suggestion is plausible. The resistivity surveys were an attempt to delineate possible conduits for the hot water.

Ramberg and Smithson (1975) and Decker and Smithson (1975) reported unusually high heat flow and a positive complete Bouguer gravity anomaly in the Las Cruces area. Decker and Smithson (1975) concluded that the positive gravity anomaly could indicate "that an excess of high density mafic rock occurs at depth in this portion of the (Rio Grande) rift." One of their models explained the excess high density with a 9-km upwarp of the crust-mantle interface. Their gravity data are indirect evidence for the possibility of a mantle-related source for the heat of the waters of both Radium Springs and Las Alturas Estates. Magnetotelluric studies have also suggested a "major magmatic intrusion" beneath the Mesilla basin at a depth between 5 and 10 km (Hermance and Pedersen, 1977).

RADIUM SPRINGS KGRA

Hydrology

Conover (1954) and King and others (1971) have discussed the ground water in the Las Cruces area. Conover's investigation was primarily concerned with the availability of shallow ground water to supplement the supply of surface water for irrigation. Based upon his findings, numerous irrigation wells were drilled in the valley floor and on the higher piedmont slopes. These wells rewarded their owners with copious amounts of water during times of drought, but they have had a marked effect on ground water levels (King and others, 1971). King and others (1971) emphasized the relationship of regional geology to the hydrologic system. Little concern with the thermal waters of Radium Springs was expressed in either report. When mentioned, the context was one of water quality (Table 12).

The valley fill and the upper member of the Santa Fe Group, the Camp Rice Formation, form the major ground water reservoir in the Las Cruces area. The Camp Rice aquifer is composed of innumerable lenses of sand, gravel and clay. Facies changes are common and may inhibit hydraulic connection between the shallow aquifer pumped for domestic and irrigation use and permeable zones lower in the section. Lower members of the Santa Fe Group are often bolson-fill deposits and are relatively impermeable (Seager and others, 1975a).

Values for the coefficient of transmissivity have been calculated to be as low as 6,000 gpd per foot for the piedmont slopes of the Santa Fe Group. Values between 30,000 and 80,000 gpd per foot warrant a "better aquifer" rating from King and others (1971). Conover (1954) suggested an average coefficient of transmissivity of 30,000 gpd per foot for the Santa Fe Group.

The Palm Park Formation of early Tertiary age underlies the Santa Fe Group and has been encountered in deep wells at Radium Springs (C. Wilson, personal

Table 12

Selected chemical analyses of ground water in the Radium Springs area, New Mexico (from Smith, 1977)

constituent	units	Radium Springs 21.1.10.213		Lindbeck 21.1.11.343 (C. Wilson, personal communication, 1976)	C.C. Rice 21.1.11.431 (after Conover, 1954)
		(after Conover, 1954) concentration	(after Summers, 1965) range	concentration	concentration
Na + K	mg/l	1160.	-	-	-
K	mg/l	-	155. - 163.	79.	-
Na	mg/l	-	1100. - 1100.	710.	-
Ca	mg/l	142.	126. - 142.	34.	216.
Mg	mg/l	23.	12. - 23.	29.	52.
HCO ₃	mg/l	426.	316. - 422.	180.	506.
SO ₄	mg/l	265.	255. - 277.	110.	284.
Cl ⁻	mg/l	1660.	1650. - 1680.	1100.	1510.
F	mg/l	4.6	4.6 - 5.7	1.1	-
SiO ₂	mg/l	71.	66. - 75.	4.5	-
B	ug/l	-	-	580.	-
Hardness as CaCO ₃ (Ca, Mg)	mg/l	449.	364. - 449.	200.	753.
Dissolved solids @ 160°C	mg/l	3540.	3540. - 3660.	2160.	3280.
Specific conductance	mmhos @ 25°C	6060.	5540. - 6100.	3840.	5760.

communication, 1976). The Palm Park is a dense volcanic conglomerate "mainly of laharic origin, but including fluvial, basin-floor, and piedmont toe-slop facies as well as sills, dikes, and minor flows" (Seager and Clemons, 1975).

Its average thickness is less than 700 m. King and others (1971) considered this complex assemblage of sediments derived from a volcanic highland to have low primary porosity. However, local lenses of gravel may be permeable. Rocks older than the Palm Park Formation have not been encountered by wells at Radium Springs.

The U. S. Geological Survey has analyzed the water from well 21.1W.11.343, less than 2 km southeast of Radium Springs. (See Smith, 1977, Appendix A for a description of the New Mexico well-numbering system; Appendix 2, this report.) This well was drilled to a total depth of 284 m but does not produce enough water to warrant pumping. The chemical analysis of a sample taken is included in Table 12. The vague driller's log from this well has been summarized by Clyde Wilson of the U.S.G.S. as follows: "Lithology mostly clay, with a few thin gravel lenses. At 259 m hit a little gravel bed where water was hot and salty ... May be similar to Radium Springs water." Another well near Radium Springs was discussed by Conover (1954):

The well of C. C. Rice (21.1W.11.431) is on the mesa beside the railroad at Fort Selden, a mile south of Radium Springs and above the valley floor. The water in this well is similar to the water of Radium Springs. Analysis of the water in the Selden Drain indicates that water with a high concentration of dissolved solids and high percentage of sodium is entering the valley in this area.

It appears that gravel stringers within the Santa Fe Group or Palm Park Formation contain water similar to that of the hot springs. The hot, saline water of Radium Springs could possibly be flowing in a deep aquifer. This possibility prompted the use of electrical soundings at Radium Springs.

Conover (1954) believed there was a hydraulic connection between the Jornada del Muerto and the Mesilla basin near Radium Springs. King and others

(1971) disagreed. They stated that "recent field work and better subsurface control indicate that the ground water does not go through the surface topographic break (near Radium Springs) ... Instead it flows northward." (King and others, 1971). This uncertainty prompted the use of total field mapping surveys at Radium Springs KGRA. Ground water within the Mesilla Valley flows to the south, like the Rio Grande.

Geology

Radium Springs is located at the northern end of the Mesilla basin, one of the southernmost grabens in the Rio Grande rift (Woodward and others, 1978). The springs emerge at the intersection of features produced by three major stages of tectonism: 1) Laramide folding and uplift, 2) Oligocene rhyolitic volcanism, and 3) late Tertiary block faulting in the Rio Grande rift. The axis of a north-trending Laramide anticline passes approximately 4 km west of Radium Springs (Figure 40) and, in the subsurface, could provide a large reservoir for the waters that emerge at Radium Springs. This postulated reservoir for geothermal fluids could be governed by many of the confirmed relations found in anticlinal oil and gas traps.

Two Oligocene volcanic centers have been mapped in the vicinity of Radium Springs. The silicic volcanism of these events gave way about 26 m.y. ago to basaltic-andesitic flows (Seager and others, 1975a). The inference from this shift is that this age marks the beginning of active extensional tectonics in the Rio Grande rift.

Evidence for active rifting from early Miocene to Pleistocene time can be found in the area immediately surrounding Radium Springs. The Pliocene appears to represent the culmination of rifting and basaltic activity. Broad intrarift basins were segmented into prominent intrabasin horsts and grabens, and basalt dated at 9 m.y. was erupted (Seager, 1975b). A narrow intrarift horst

Figure 40. Late Eocene subcrop map, Radium Springs area (after Seager, 1974b).

separating the upper Mesilla Valley from the Jornada del Muerto basin to the northeast formed during this most recent stage of uplift. It is not likely that the fault which bounds the horst is the same fault along which Radium Springs emerge (Seager, personal communication, 1976). The gravity data of Ramberg and Smithson (1975) and the magnetotelluric data of Hermance and Pedersen (1977) suggest that an upwelling of magma at a depth as shallow as 5 km may be the source of heat for the hot springs.

The geologic studies by Seager and associates suggest the following hypothesis for accumulation and upward migration of hot water at Radium Springs. Porous strata in the Laramide anticline could form a channel for the migration and accumulation of low density thermal fluids. Paleozoic limestones, dolomites and clastics exposed in the Robledo Mountains approximately 6 km south of Radium Springs are folded by the anticline. A wide variety of stratigraphic traps in the Paleozoic section of southern New Mexico have been discussed by Kottowski (1963). Reefs, crinoidal limestones, wedgeouts, bioherms, porous sandstone lenses and other possible traps have all been observed and may exist in the subsurface at Radium Springs. Fracturing of the formations during uplift, or subsequently during volcanic episodes or late Tertiary normal faulting could have produced secondary porosity. Solution openings may exist in formations like the potentially cavernous Caballero Limestone.

The Laramide anticline was deeply eroded during the Eocene and was covered by Palm Park Formation. Thus the folded and permeable Paleozoic rocks are unconformably overlain by an impermeable volcanic conglomerate. The reservoir potential of the anticline may have been substantially improved by this angular unconformity.

Hot water seeps out of the banks of the Rio Grande near Radium Springs. The water appears to rise along a late Tertiary fault. A pair of mapped faults curve through Radium Springs; the seeps appear to be associated with the westernmost of these faults (Figure 41).

Figure 41. Representative late Tertiary faults in the Radium Springs area (after Seager, 1974b; Smith, 1977).

A schematic northeast-southwest cross section through Radium Springs (A-A' of Figures 40 and 41) is shown as Figure 42. The cross section passes near the bipoles of the electrical survey. The location of lithologic units below the angular unconformity, shown as a wavy line, is taken from Figure 40. The faults that extend to the surface are taken from Figure 41. An intrarift horst inferred from geophysical data is superimposed the flank of the anticline on the right side of the figure.

This figure illustrates the conceptual model for the accumulation and upward migration of hot water at Radium Springs. Several hundred meters of potentially porous Paleozoic marine sediments may have been folded during Laramide time. The inferred anticline was eroded and covered by a thick, impermeable volcanic conglomerate. A combined structural-stratigraphic trap may have formed. During the late Tertiary, rifting may have penetrated the trap. A fault bounding a narrow intrarift horst may allow hot water trapped there to continue its upward migration. Water rising along this fault may be contained in an aquifer inferred from resistivity data. From this aquifer the water may rise under artesian heat at Radium Springs. The water may absorb heat from a shallow magmatic intrusion, as discussed by Hermance and Pedersen (1977).

Electrical Studies

Introduction. A two-phase electrical resistivity exploration program was conducted at Radium Springs KGRA (Figures 14, 43, and Table 8). The first phase consisted of a pair of regional total-field bipole-dipole reconnaissance surveys. The second phase incorporated three asymmetric Schlumberger and equatorial soundings from a triangular array of 400-m long bipoles, 1.5 km east of the resort. Results of the surveys were published by Jiracek and Smith (1976); Smith (1977; Appendix 2, this report) has described a conceptual model of the subsurface compatible with the electrical surveys and mapped geology.

Figure 42. Schematic cross section of the Radium Springs area (from Smith, 1977).

Figure 43. Radium Springs study area.

Direct current mapping. Figures 44 and 45 are the two total-field apparent resistivity maps generated from 2-km bipoles located in the Jornada del Muerto basin near Radium Springs. Each survey covered an area of approximately 75 km². A producing water well at T.20S., R.1W., sec. 26.122 on New Mexico State University's Jornada Animal Husbandry Range served as a common electrode for the bipoles. The upper two-thirds of Figures 44 and 45 covers a corner of the vast Jornada del Muerto; the Mesilla basin and the Mesilla Valley begin at Radium Springs and extend to the southeast along the Rio Grande (Figure 43).

The area in the southeast corner of Figures 44 and 45 displays the highest values of apparent resistivity (~40 ohm-m). These resistivities are associated with the Dona Ana Mountains (Figure 43), a mid-Tertiary caldera complex (Seager and others, 1976). Both the exposed monzonites and tuffs are characteristically highly resistive and impermeable. These rocks may extend in the subsurface as far north as the steepest resistivity gradient on the eastern edge of Figure 44. This gradient coincides with the location of a posulated "Jornada Fault" (Seager, 1975a) where the intrusives would be downdropped to the north.

The broad low-resistivity region in the northeastern part of both figures is undoubtedly associated with the Jornada del Muerto (Figure 43). Its ground water contains much gypsum and grades from good (<50 ppm sulfate) near the Dona Ana Mountains to nonpotable (>1560 ppm sulfate) at the northern edge of the figures (King and others, 1971). The low resistivities observed are interpreted to be indicative not of geothermal phenomena but of the quality and thickness of the water-saturated strata. The deepest soundings in the Jornada are mapped in the northeast corner of Figure 45 along the equator of the bipole. The higher resistivity values recorded there may reflect the resistive basement.

Low resistivities such as the less than 5 ohm-m values observed near Radium Springs are expected at the site of a hydrothermal geothermal anomaly.

Figure 44. Total field apparent resistivity map of Radium Springs study area derived from east-west bipole transmitter.

Figure 45. Total field apparent resistivity map of Radium Springs study area derived from north-south bipole transmitter.

These low resistivities may reflect the presence of a large body of hot, saline water extending south in the Mesilla Valley (Figure 43). However, it is possible that conductive clay causes this low resistivity pattern.

In Secs. 35 and 36, T.20S., R.1W., the total field patterns form a 15-20 ohm-m saddle. This saddle separates the low resistivity region of the Jornada del Muerto from the low resistivity region surrounding Radium Springs. Both figures show the 15-20 ohm-m saddle to have a distinct northwest-southeast trend. This trend continues to the east where it links with the higher resistivities associated with the Dona Ana Mountains. The resistivity saddle suggests basement structure separating the Jornada basin from the Mesilla basin, possibly an intrarift horst (Seager, 1975a). The total field data, therefore, are interpreted to indicate the location of a barrier to groundwater flow. This precludes any significant connection between the hot springs of Radium Springs and the vast potential reservoir to the north.

Direct current sounding. The second phase of resistivity exploration attempted to discern the cause of the low resistivity anomaly that surrounds Radium Springs and extends south down the Mesilla Valley. Three combined asymmetric Schlumberger and equatorial soundings were made using 400-m bipoles. The bipoles were located on the piedmont slope above the valley roughly 1.5 km due east of the hot springs. They appear as small triangles near the bottoms of Figures 44 and 45. One sounding ran due west through Radium Springs; a second passed south through Fort Selden; the third bisected the other two, entering the valley near Leasberg Dam.

The line that passed nearest to Radium Springs passed over a resistive dike of rhyolitic tuff of Oligocene age near the spring house of the resort. The dike deformed the sounding curve, making it unsuitable for layered

interpretation. However, if the effect of the highly resistive dike were smoothed out of the curve, there is a virtual point-for-point correspondence between the data from all three soundings (Smith, 1977 and Appendix 2).

This close agreement among three sounding curves reveals a pronounced lateral electrical homogeneity in this part of the Mesilla basin. This means that, except for the outcrop near the hot springs, there are no shallow structural inhomogeneities within the Mesilla basin near Radium Springs.

The sounding data and interpreted model (Zohdy, 1973a) from the line that ran south through Fort Selden are shown in Figure 46. The upper two layers, with resistivities of 280 and 35 ohm-m, extend to a total depth of 107 m. Of the two, the first can be expected to reflect the unsaturated piedmont slope sediments above the valley. The second reflects water-saturated Santa Fe Group within the valley. This interpretation does not mimic known conditions within the Mesilla Valley, where the soil is saturated within a meter of the surface. It must be remembered that this survey is not a conventional Schlumberger sounding centered in the valley but is an equatorial sounding from a bipole more than 1 km away. At shallow depths, therefore, the data reflect the more resistive piedmont slope deposits of the uplands and not the near-surface waters within the valley fill.

The second group of interpreted layers displays very low resistivity values (4, 1.6 and 6 ohm-m) extending to a depth of 289 m. This 182-m thick conductive zone could possibly be composed entirely of clay. However, as all three soundings were conducted less than 2 km from Radium Springs, it is likely that part of it contains hot saline water.

The final two layers of progressively greater resistivities may represent the Paleozoic sequence and electrical basement, presumably Precambrian rock of the type that crops out north of Radium Springs at San Diego Mountain (Seager, 1975a).

Figure 46. Combined asymmetric Schlumberger and equatorial bipole-dipole sounding at Radium Springs and interpreted seven-layer model.

Conclusions

Bipole-dipole surveys have demonstrated that the southern Jornada del Muerto basin is structurally separated from the Mesilla basin by an inferred intrarift horst. This eliminates the Jornada del Muerto as a reservoir for the hot water of Radium Springs. Each of the three soundings located a 180 m-thick conductive zone at a depth of approximately 100 m. Parts of this zone may be saturated with hot saline water. The uniformity of the sounding data indicates that the interpreted aquifer may extend south of Radium Springs. The hot springs at Radium Springs are artesian and may be an isolated surface expression of the fluids contained in the inferred aquifer. The following is advanced for hypothesis for the accumulation and upward migration of thermal waters at Radium Springs. Waters may be rising along a late Tertiary fault bounding the intrarift horst and accumulating in a deep anticlinal trap. A possible heat source for the region is a shallow (5 km deep) magmatic intrusion such as has been suggested to explain nearby magnetotelluric data (Hermance and Pedersen, 1977). Such intrusions of late-Tertiary age or a locally upwarped mantle have been proposed by Decker and others (1975) to account for the heat flow and gravity anomalies in the area.

An estimate of the heat content in the Radium Springs thermal reservoir can not be made since our surveys did not define the extent of the aquifer to the south. The geochemical data published by Swanberg (1975) indicates that the Radium Springs KGRA may be a part of a nearly continuous geothermal system extending from San Diego Mountain to the north along the Rio Grande south into Texas and Mexico. This concept is discussed below in the section on Las Alturas Estates.

LAS ALTURAS ESTATES

Geology and Hydrology

Wells at Las Alturas Estates yielded water with temperatures ranging from 25 to 45°C (Table 13). While these wellhead temperatures are too low to be applied to the generation of electricity, they are sufficient for space heating and other applications.

Las Alturas Estates is less than 3 km southwest of Tortugas Mountain, locally called 'A Mountain', a 900-m high dome of Hueco Limestone of Permian age that emerges from Santa Fe Group and more recent piedmont-slope alluvium (Figure 47). The limestone outcrop covers an area of roughly 2.5 km². The name Tortugas, the turtle, fits it well.

Tortugas Mountain, Goat Mountain and the Dona Ana Mountains near Radium Springs form a distinct NNW lineament paralleling the Mesilla Valley. A buried bedrock high connecting the three aligned mountains has been encountered in several water wells along Highway 70, 12 km north of Las Alturas Estates. The down-hole data of King and others (1971) revealed that the crest of the bedrock high is composed of andesitic rock, possibly the Palm Park Formation. If the history of the Las Alturas Estates area is similar to that proposed for the Radium Springs area, the buried bedrock high could be a Basin and Range horst block between the Mesilla basin on the west and the shallow southeastern arm of the Jornada del Muerto basin on the east. If this interpretation is correct, the horst would be the southernmost link in a chain of intrarift horsts that bounds the Jornada del Muerto basin. It is a narrow, linear and persistent electrical feature north of Tortugas Mountain (C. Wilson, personal communication, 1976). Tortugas Mountain is located at the southern end of this inferred chain of horsts.

Table 13

Selected chemical analyses of ground water in the Las Alturas Estates area, New Mexico
(from Smith, 1977)

constituent	units	Las Alturas Estates	City of Las Cruces	Las Cruces Country Club
		(C. Wilson, personal communication; 1976)	well #2 (R. Lepp, personal communication, 1977)	(after Conover, 1954)
		23.2.34.412	23.2.21.223	23.2.6.322
		concentration	concentration	concentration
Na + K	mg/l	-	-	94.
K	mg/l	-	11.	-
Na	mg/l	180.	110.	-
Ca	mg/l	66.	142.	58.
Mg	mg/l	13.	31.	17.
HCO ₃	mg/l	319.	368.	232.
SO ₄	mg/l	140.	150.	227.
Cl ⁻	mg/l	170.	252.	153.
F	mg/l	-	0.35	0.3
SiO ₂	mg/l	-	38.	-
B	ug/l	-	170.	-
Hardness as CaCO ₃ (Ca,Mg)	mg/l	220.	481.	441.
Dissolved solids	mg/l	-	1172.	747.
Specific conductance	mmhos	1020.	1585.	1210.

Figure 47. Geology of the Las Alturas Estates area (from Smith, 1977).

The reconnaissance geologic map of Kottlowski (1960) shows two faults associated with Tortugas Mountain, one on the northeast and the other on the southeast (Figure 47). Neither fault is shown to continue beyond the limestone outcrop, but they may be present below sedimentary cover. Gravity data detect the fault on the northeast (Figure 39). There is no indication that hot water is migrating from depth along either fault. The limestone on Tortugas Mountain dips 15° W. It is possible that the limestone continues to dip west below the hot wells.

King and others (1971) showed the water table at Las Alturas Estates to dip southwesterly, away from Tortugas Mountain and towards the Rio Grande. The hot water is contained in the alluvial-fan facies of the Santa Fe Group. These sediments presumably overlie the less permeable Hueco Limestone. It is plausible that the hot water encountered at Las Alturas Estates migrates from depth along deepseated faults associated with Tortugas Mountain. The University of New Mexico resistivity surveys studied the area between the hot wells and Tortugas Mountain in detail in an attempt to discover structures controlling the hot water.

Electrical Resistivity Studies

Introduction. The proximity of New Mexico State University to domestic wells producing warm water at Las Alturas Estates motivated a detailed electrical exploration program in this target area (Figure 37). The first activity, in 1976, consisted of reconnaissance bipole-dipole mapping of an area over 30 km^2 surrounding two bipole sources east of the hot wells (Figure 38). The mapping was followed by a pair of orthogonal Schlumberger soundings centered at the hottest well (45°C , 108 m deep; Summers, 1976) located at T.23S., R.2E., Sec. 34.214 (Figure 38). Attempts to better define the geothermal reservoir were

made in 1977 by positioning a current electrode near the bottom (105 m) of the second hottest well (36.5°C; C. Wilson, personal communication, 1977) to the south (T.23S., R.2E., Sec. 34.412, Figure 38). Downhole inaccessibility of the hotter well dictated use of the alternate well. Downhole-remote and surface-remote mapping enclosed an area of about 15 km² centered about this well site. Two dipole-bipole lines using spacings of 300 m with profile lengths of 4.5 and 3.2 km were also measured during 1977 (Figure 38). Findings from the 1976 field season were summarized by Smith and others (1977) and analyzed by Smith (1977 and Appendix 2). More quantitative interpretation of the combined resistivity results was presented by Jiracek and Gerety (1978) at the 1978 Geothermal Resources Council meeting, by Hohmann and Jiracek (1979), Morgan and others (1980), and Gerety (1980; Appendix 2, this report).

Direct current soundings. Crossed Schlumberger soundings centered at the hottest well (Figure 38) are presented in Figure 48, with five layer interpretations using an inversion method developed by Zohdy (1973a). Close scrutiny of the field results reveals that beyond an electrode spacing of about 30 m, the 78° sounding systematically yields apparent resistivity values less than the 348° sounding. This is considered to be a consequence of the paradox of anisotropy (Keller and Frisknecht, 1966) whereby the minimum apparent resistivity is measured perpendicular to the strike of the conductive body. Hence, the conductive zone extends more north-south than east-west. Interpreted results in Figure 48 have not been corrected for anisotropy; however, the conductive-layers (8 and 9 ohm-m) are identified with the thermal reservoir. Considering all of the results (including well data and the dipole-dipole results to be described), the 78° sounding is considered more representative of the section. Thus, the shallow geothermal reservoir is estimated to extend in

Figure 48. Crossed Schlumberger soundings at Las Alturas Estates and interpreted five-layer models (from Smith, 1977).

depth from approximately 94 to 255 m.

To further define the conductive zone associated with the geothermal reservoir, two dipole-dipole profiles were surveyed across the Las Alturas prospect. The lines were oriented (Figure 38) to better define the east-west extent of the conductive target. Figures 49 and 50 present the observed dipole-dipole pseudosections together with two-dimensional numerical model calculations (Dey and Morrison, 1976). The results in these figures are in good agreement with the Schlumberger results (Figure 48). Furthermore, the independent two-dimensional modeling allows more quantitative conclusions to be drawn. For example, the geothermal zone (~ 10 ohm-m) clearly extends more to the east from the hot well in Figure 49 than west; the southwestern extent of the layer is terminated laterally 600 m from the well at station 9 by a resistive (~ 50 - 100 ohm-m) barrier. The zone is bounded on the east (station 42) by a very prominent resistive block (~ 300 ohm-m), the depth to the top of the 10 ohm-m layer varies from about 40-110 m, and the bottom of the zone appears to be about 300 m. The conductive geothermal reservoir is also evident on the northern dipole-dipole line (Figure 50) extending from station 4 to station 28. The 5 ohm-m resistivity modeled between stations 14 and 20 (Figure 50) is the lowest on either profile and may indicate higher temperatures in this region.

Direct current mapping. Two total field apparent resistivity maps generated from the pair of bipoles east of the hot wells at Las Alturas Estates and south of Tortugas Mountain are presented in Figures 51 and 52. The bipole of Figure 52 is oriented broadside to the hot wells; the bipole of Figure 51 is oriented more in line with the wells. In Figures 51, 52 (and Figures 54, 55) regions of apparent resistivity less than 60 ohm-m are shaded by a dot pattern.

Conductive regions (< 60 ohm-m) mark the area of the hot wells in both Figures 51 and 52. This zone is sharply circumscribed by a resistive pattern

Figure 49. Dipole-dipole pseudosection sounding at Las Alturas Estates-south and two-dimensional model calculations (from Jiracek and Gerety, 1978).

Figure 50. Dipole-dipole pseudosection sounding at Las Alturas Estates-north and two-dimensional model calculations.

Figure 51. Observed total field apparent resistivity map of Las Alturas Estates study area derived from east-west bipole transmitter (from Hohmann and Jiracek, 1979).

Figure 52. Observed total field apparent resistivity map of Las Alturas Estates study area derived from north-south bipole transmitter (from Hohmann and Jiracek, 1979).

(>60 ohm-m), especially in Figure 51, on the east, north and west sides of the survey area. Three-dimensional modeling (Hohmann and Jiracek, 1979) was applied interactively to these results to determine to what extent the observed patterns reflect the true subsurface resistivity distribution, i.e., the areal extent of the shallow geothermal reservoir.

Figure 53 shows a plan view of the three-dimensional model used to approximate the conductive geothermal reservoir. This model was defined from the combined Schlumberger and dipole-dipole (Figures 48, 49, 50) modeling and by a comparison of the observed bipole-dipole patterns with theoretical results presented by Hohmann and Jiracek (1979). The reservoir is approximated by a slab of 10 ohm-m material which is 100 m deep and 500 m thick. The body has an approximately north-south length of 6 km and east-west width of 2.5 km. The more complex resistive body of 300 ohm-m to the east of the conductive slab in Figure 53 models the resistive limestone of Tortugas Mountain (Seager and Brown, 1978) and its buried extension to the south. The conductive and resistive slabs are immersed in a half-space of 75 ohm-m. The simple model presented in Figure 53 does not attempt to detail either the more complex near-surface (<100 m) variations or the conductive basin to the northeast beyond Tortugas Mountain (Figures 51 and 52). This latter conductive feature is discussed below.

A comparison of the theoretical results in Figures 54 and 55 with the field data of Figures 51 and 52 reveals a remarkable similarity. This is more evident when comparing Figures 51 and 54. It is apparent that the actual body is wider than the 2.5 km body modeled and may extend farther to the south. However, the 60 ohm-m contour may be considered as very nearly outlining the body in Figures 51 and 54. Again, it is emphasized that no attempt was made to model the regions near the bipole electrodes which reflect shallow resistivity variations. The main interest was in duplicating the major patterns of the

Figure 53. Simple three-dimensional resistivity model of Las Alturas Estates study area (from Hohmann and Jiracek, 1979).

Figure 54. Calculated total field apparent resistivity map of Las Alturas Estates study area derived from east-west bipole transmitter (from Hohmann and Jiracek, 1979).

Figure 55. Calculated total field apparent resistivity map of Las Alturas Estates study area derived from north-south bipole transmitter (from Hohmann and Jiracek, 1979).

field results using all available constraints, e.g., Schlumberger, dipole--dipole and drilling results.

Notice that the conductive zone is not nearly so well-defined in Figures 52 and 55. Theoretical models presented by Hohmann and Jiracek (1979) expose the difficulty in delineating conductive boundaries when both current electrodes are placed over the body. This is the case with the north-south bipole transmitter at Las Alturas Estates. The nearly east-west bipole source in Figures 51 and 54 has a more desirable configuration, with only one electrode over the body; better delineation of the anomaly would have been accomplished with both dipole sources well removed from the body. The important problem of proper positioning of the bipole sources away from the conductive target can be solved by limited detailed surveying. For example, by dipole-dipole profiling, prior to bipole-dipole mapping. This aspect of doing some degree of detailed surveying prior to bipole-dipole reconnaissance is contrary to the usual field practice.

Northeast of the high resistivity lobe at Tortugas Mountain, both Figures 50 and 52 display resistivities less than 30 ohm-m. These lows lie within a small part of the southern arm of the Jornada del Muerto basin (Figure 37) and are characteristic of clay-rich, water-saturated basin fill. The steep gradients in apparent resistivity between the Jornada del Muerto and Tortugas Mountain suggest the location of a high-angle fault. The fault, called the Jornada fault, is also indicated by gravity data and interpreted by geologic mapping (Seager and Brown, 1978).

In Figures 49, 50, 51 and 52 the western boundary of the high resistivity lobe surrounding Tortugas Mountain forms a distinct, sharp and linear gradient. The location of the gradient is approximately the same in all figures. This gradient and the combined modeling suggest a fault west of Tortugas Mountain.

This fault may govern the occurrence of hot water at Las Alturas Estates (Jiracek and Gerety, 1978). The feature is consistent with detailed gravity data (Dicey and others, 1979) and may be part of the late Tertiary block faulting that raised Tortugas Mountain along the Jornada fault. The faulting may have been influenced by an earlier caldera margin which is inferred through the area (Seager and Brown, 1978). The older rocks of Tortugas Mountain are interpreted as an exposed remnant of this caldera wall which extends intermittently southeast and as far to the east (~20 km) as the Organ Mountains.

Applying the principle that electrical current introduced directly into a conductive geothermal reservoir experiences greater channeling compared to a surface source, a down-hole remote mapping survey was performed at Las Alturas Estates. The downhole method is really a modification of standard bipole-dipole mapping. At Las Alturas Estates one electrode was positioned 105 m downhole (D); the other emplaced remotely (R) on the surface 3.02 km away (Figures 38, 56). This bipole source was supplemented by another using an electrode on the surface (S) near the wellhead with the same remote (R) contact (Figure 57). The D-S source combination was not actually energized, but simple subtraction of the D-R and S-R results numerically yields this combination. However, since the D-R and S-R results closely match each other (Figures 56 and 57) the numerical subtraction process propagates small measurement errors excessively into the final D-S results (Gerety, 1980; Appendix 2, this report).

Receiver locations for the S-R and D-R current sources were located on survey lines radiating from the 36.5°C well (Figures 56 and 57). Voltage measuring dipoles at each receiver location were occupied in both the radial and tangential directions. The various geometrical combinations enable several different apparent resistivity maps to be computed and compared. These include radial, tangential and total electric field S-R, D-R and D-S maps. The radial

LAS ALTURAS ESTATES

TOTAL FIELD APPARENT RESISTIVITY (OHM-M) DOWNHOLE-REMOTE CONFIGURATION

Figure 56. Observed downhole-remote total field apparent resistivity map of Las Alturas Estates (from Gerety, 1980).

LAS ALTURAS ESTATES

TOTAL FIELD APPARENT RESISTIVITY (OHM-M) SURFACE-REMOTE CONFIGURATION

Figure 57. Observed surface-remote total field apparent resistivity map of Las Alturas Estates (from Gerety, 1980).

field S-R and D-R maps at Las Alturas Estates were presented by Jiracek and Gerety (1978). The corresponding total field maps were calculated by Gerety (1980 and Appendix 2) and are displayed in Figures 56 and 57.

The figures illustrate an expected agreement at large distances from the drill hole and distinct differences at short spacings. These differences include effects due to current channeling in the geothermal aquifer which, as seen from the contour patterns, trends more north-south than east-west; this was established previously (Figures 51 through 55). Numerical three-dimensional modeling, not presented here, has been used to study the patterns in Figures 56 and 57. Results expose considerable complexity which is a function of reservoir size, shape, depth, lateral resistivity contrasts with surrounding material and downhole (D) electrode position. Judging from a simple conductive model in a resistive half-space (Figure 53), the patterns in Figures 56 and 57 may be explained if the well is situated on the west side of the reservoir with the downhole electrode (D) in Figure 56 well into the conductive zone. The zone trends NNW-SSE and is much more extensive than the conductive apparent resistivity anomaly (<20 ohm-m). Both figures map a resistive feature (>40 ohm-m) about 1 km west of the well site. This feature is evident at dipole-dipole station 6-9 (Figure 49) and presents a barrier not included in the simple model of Figure 53.

The results of Figures 56 and 57 do not indicate any geothermal water preferentially flowing from individual conduits along the suggested fault on the east side of the area. However, the contours of the downhole-remote (D-R) configuration (Figure 56) do not close to the north or south, indicating an extended conductive (geothermal) zone in these directions. The surface bipole-dipole results (Figures 51 through 55) indicate the termination north of area surveyed in Figures 56 and 57; no clear southern termination is evident.

Conclusions. No ultimate heat source has been located by the electrical resistivity surveys completed at Las Alturas Estates. The shallow (~5 km deep) magma hypothesis suggested to explain nearby magnetotelluric results (Hermance and Pedersen, 1977) is certainly a possible heat source. However, deep circulating water rising along a fault is considered more likely. Geochemical data from the Las Alturas wells (Swanberg, personal communication 1978) yield SiO_2 and Na-K-Ca temperatures of 109°C and 179°C , respectively. A mixing model applied to the silica data suggests an estimated basal temperature of over 150°C . Given these geochemical temperatures, it is likely that the shallow thermal reservoir at Las Alturas Estates is a manifestation of deeper circulation. Electrical resistivity studies suggest a westward-dipping fault along the western margin of Tortugas Mountain and its buried extension to the south as the circulation zone. Shallow waters would consequently be hotter toward the eastern margins of the survey area. This original suggestion (Jiracek and Gerety, 1978) has been proven correct by subsequent drilling results (Morgan and others, 1979). Highest temperature gradients were measured east of the original hot wells; a maximum temperature of 62.5°C was encountered at 300 m depth near dipole-dipole station 17. (Figure 50). This is the site of the lowest modeled resistivity (5 ohm-m) and furnishes excellent agreement between resistivity and drilling results. High geochemical temperatures extend for considerable distances (10's of km) NNW and SSE of the survey area (Swanberg, 1976), indicating that the Las Alturas thermal anomaly may be part of a much more extensive system. Using the resistivity data and measured temperature results, however, one may draw some conclusions concerning the total heat content of the shallow reservoir discovered at Las Alturas Estates. The following calculation was presented in 1978 by Jiracek and Gerety. New data do not substantially change the calculation, which is based on the method

described in USGS Circular 726 (Renner and others, 1976). Here the total heat content is calculated as the product of the assumed volume, volumetric specific heat of the reservoir, and average reservoir temperature in $^{\circ}\text{C}$ above mean annual surface temperature.

Using the following considerations, an estimate of the heat content in the shallow thermal aquifer at Las Alturas Estates can be made:

- 1) Volume. An estimated east-west extent of 3 km is based on the conductive anomaly measured by bipole-dipole and dipole-dipole findings; an estimated north-south extent of 6 km is defined by high resistivity bipole-dipole results to the north and an equal distance south from the 36.5°C well in agreement with the downhole (surface)-remote mapping; an estimated average depth of 75 m to the top, and 300 m to the bottom, of the conductive geothermal zone is determined from Schlumberger and dipole-dipole results. The volume thus calculated equals 4.05 km^3 .

Truncation of the geothermal zone at 3 km to the south is conservative, since a few additional Schlumberger soundings (Young, 1978; Jackson, 1976) sounded a similar conductive horizon at a distance of 5 km south. There is also the possibility of a connected system extending even farther south and north. Also, due consideration must be given to the well-known fact that some nongeothermal zones (e.g. clays) exhibit low resistivity values indistinguishable from geothermal reservoirs.

- 2) Volumetric specific heat. Porosity of the geothermal zone is estimated at 30 percent. A porosity estimate of 30 percent is in agreement with Archie's law (Meidav, 1970) when the known water resistivity of 3 ohm-m is used with the interpreted reservoir value of 10 ohm-m. Using the specific heat of water as $1.0 \text{ cal/cm}^3^{\circ}\text{C}$ and of average rocks, 0.6 of this value, the volumetric specific heat is calculated as $0.72 \text{ cal/cm}^3^{\circ}\text{C}$.

3) Reservoir temperature above mean annual. The mean annual temperature in this area is 17°C; average shallow reservoir temperature is taken as 50°C, which is a reasonable compromise between the measured temperatures (maximum well temperature of 45°C) and a gradient of about 200°C/km. The geothermal gradient is estimated using the mean annual temperature of 17°C and an approximate mean for the temperature at 100 m depth (40°C). If a 200°C/km gradient persists to depth, it would yield a higher average reservoir temperature; however, 50°C is considered a conservative estimate for the total 18 km² area. (Note: the subsequent drilling of Morgan and others (1979) found shallow temperature gradients (<30 m) as large as 446°C/km.) Average temperatures in the water saturated zones of the two deep holes (~300 m) were roughly 50 to 60°C.

4) Approximate heat content calculation. Using the above estimates one calculates

$$\text{Heat content} \approx 4 \times 10^{15} \times 0.7 \times (50-17) \text{ cal, or}$$

$$\text{Heat content} \approx 9 \times 10^{16} \text{ cal}$$

$$[(3.8 \times 10^{17} \text{ joule; } 3.6 \times 10^{14} \text{ Btu})]$$

in the shallow reservoir at Las Alturas Estates.

Conclusions

The Las Alturas thermal anomaly is probably caused by deep circulating water rising along a west-dipping normal fault of Pliocene(?) age which forms the western margin of Tortugas Mountain and its buried extension to the south. The anomaly probably extends many kilometers north and south of the study area

and may represent part of a major thermal anomaly along the eastern side of the Mesilla Valley.

The volume of the shallow geothermal reservoir at Las Alturas Estates is estimated to be at least 4 km^3 , with a total heat content of at least 3.8×10^{17} joules. Subsequent drilling has shown excellent agreement between the actual reservoir and the proposed geothermal reservoir as determined by electrical surveys.

Alum Mountain

GEOLOGY

Introduction

The volcanic complex of Alum Mountain is located in the Gila Primitive Area, Grant County, New Mexico (Figure 58). The complex consists of hornblende-plagioclase and pyroxene-plagioclase andesite flows and breccia; ash falls and ash-fall breccia; volcaniclastic sediment and sandstone; agglomerate flows; and latites and rhyolites. All units exhibit varying degrees of hydrothermal alteration, silicification, propylitization or secondary mineralization. Alum Mountain itself represents part of a volcanic center that includes the Copperas Canyon area to the south, and Gila Flats to the east and west. The section can be divided into three parts: lower andesite and andesite breccia; middle andesite and ash falls; and upper agglomerate, latite, and rhyolite intrusives.

Lower Andesite and Andesite Breccia

Hornblende-plagioclase and pyroxene-plagioclase andesite and andesite breccia crop out along the Gila River both east and west of Alum Mountain. Breccias are approximately flat-lying but are not laterally continuous. West of Alum Mountain these breccias are locally filled with moderate to well sorted, moderately rounded quartz sandstone. East of Alum Mountain a 1-2-m thick breccia is areally extensive and is overlain locally by thin sandstone, volcaniclastic sediment and basaltic andesite breccia; these rocks are part of Ratte and Gaskill's (1975) younger andesitic and latitic flows of Miocene (?) age. The andesite breccias are hematite stained and locally zeolitized.

Figure 58. Physiographic sketch map of part of southwestern New Mexico, showing location of Alum Mountain area. See Ratte and Gaskill (1975) for details of regional geology, and Krier (1980) for geology of Copperas Prong.

Andesites appear to be locally derived, with vent structures and dikes cropping out along the Gila River west of Alum Mountain. Andesites show limited hydrothermal alteration; vugs and vesicles commonly are filled with zeolites, including heulandite, chabazite, stilbite, soda stilbite and calcic-mordenite (Northrop and others, in preparation). Zoning in these zeolites, while not understood, is extensive, extending north and east along the Gila River beyond Lyons Lodge along the east fork of the Gila River. Because the Bloodgood Canyon Rhyolite Tuff (Ratte and Gaskill, 1975) is not zeolitized in this area, a question of the age of these rocks arises. Ratte and Gaskill (1975) group some of the zeolitized andesites north of Alum Mountain into a group younger than the Bloodgood Canyon Rhyolite Tuff, yet the more permeable Bloodgood Canyon tuff shows no evidence of hydrothermal alteration or zeolitization where it crops out above the middle part of the Alum Mountain section.

Middle Andesite and Ash Fall

The middle part of the section is primarily ash falls and ash-fall breccia with some interlayered andesite flows and dikes. This part of the section is best exposed in Alum Canyon and the smaller canyons west of Alum Mountain. Alum Mountain itself is a thick accumulation of ash fall material which thins in all directions. These ash falls are composed of angular to subrounded glass shards in a clay matrix. The rounding, degree of welding and amount of clay matrix may be a direct measure of the amount of hydrothermal alteration in the area. However, in some areas the ash falls are highly silicified, tending to preserve textures and, at first appearance, indicate a high degree of welding.

It is difficult to determine the lateral extent of many of these units; however, one horizon has been reworked, bedded and silicified, and is quite distinct. This bedded ash fall crops out in three areas: on the west side of

Alum Mountain, in a road cut of New Mexico Highway 15 east of Copperas Peak and on the south sides of both Copperas Peak and Buck Hannen Mountain. There is also float of this unit on the north side of the Gila River, below where the Bloodgood Canyon Rhyolite Tuff crops out. This unit is thickest at Alum Mountain and thins substantially to the south.

Ash-fall breccias occur primarily in two locations on the east side of Alum Canyon and near the top of Alum Mountain. These breccias are highly silicified and are therefore quite resistant to weathering. The outcrops on the east side of Alum Canyon stand out as circular features, suggesting they may represent remnants of ash-fall vents. Other breccias in this part of the section contain both ash-fall material and andesite, often as andesite bombs. These units are highly silicified and may also represent eruptive centers. Sinter deposits, ash-sand mixed units, alum, alunite and possibly other sulfate minerals crop out locally in this area.

Andesites occur as localized flows and dikes, and as inclusions in ash-fall units. These andesites interfinger with ash falls and contain ash-fall material as inclusions, indicating a contemporaneous eruptive period. These andesites exhibit varying degrees of hydrothermal alteration, from minor replacement of feldspar phenocrysts to complete alteration of the andesites to clay minerals.

Upper Agglomerate and Latite

The agglomerate of the upper part of the section is made up of fragments of latite, latite vitrophyre, and andesite ash and pumice; it contains sand and clay as well as phenocrysts of quartz and biotite. Locally there is evidence of underlying, thin "lake bed" sediments, and small areas of thicker pyroclastic sediments and poorly sorted lithic-rich sandstones. This unit is exposed in many road cuts on New Mexico Highway 15 from north of Copperas Peak to well

north of the Copperas Vista overlook and continues east into Gila Flats. The latites, including vitrophyres and local rhyolite intrusives, overlie or intrude the agglomerate east of Alum Canyon, but at Alum Mountain lie immediately on ash units of the middle part of the section. In all cases the base of the latite flows are marked by a thin opalized layer. Latite domes below and to the west of Buck Hannen Mountain intrude the agglomerate and are not opalized; they are connected by dikes to the flows on top of Copperas Peak. These latites erupted as small flows along northwest-trending linear zones which probably represent the eastern extension of regional faults shown by Ratte and Gaskill (1975). These latites generally show only limited hydrothermal alteration, including the opalized base, local bleaching and hematite staining; however, west of Copperas Peak, associated vitrophyres are extensively propylitized. This alteration pattern suggest ongoing alteration processes and contradicts Ratte and Gaskill's proposed disconformity at this boundary.

Alteration

Alteration in the lower andesite is not extensive and is generally directed along breccia flows where permeability was greatest. The alteration is primarily argillic alteration of the matrix, hematite staining, and locally zeolite mineralization. Other than widespread zeolite mineralization, alteration of andesite flows is restricted to areas of vent structures and is most intense in highly fractured zones along or near contacts with breccias. This alteration includes argillic alteration, silification, veins and veinlets of carbonates, quartz and(or) opal, and zeolite mineralization.

Alteration in the middle ash falls is much more intense and complex. Fluid paths were controlled by ash fall and ash-fall breccia units. Andesites are usually altered inwards from flow boundaries in contact with ash, with the extent of alteration controlled by the relative amounts of phenocrysts and groundmass. Dense chill margins away from ash units are seldom altered. Where alteration actually cross cuts andesites, it does so in relatively narrow conduits, probably controlled by jointing or major fractures.

Alteration products include clay minerals, alum, alunite, gypsum and possibly other sulfate minerals. In late-stage faulting in this zone, hematite and minor pralomolane veins occur locally. It is likely that the alum and any other highly soluble species have been reconcentrated by modern groundwater; however there is little evidence to support or refute this idea. Intense silicification of the most highly permeable units, with the presence of sinter deposits and ash-sand units, suggest these alteration processes were active while these units were at the surface. Alteration up into the base of the overlying latites further suggests that alteration continued for some time. Alunite replacing plagioclase phenocrysts in andesite indicates the presence of an early oxidized sulfur species. The extensive sulfate occurrences and the presence of hematite and absence of metal sulfides is evidence for a sulfate geothermal system, giving rise to hopes of chemical and stable isotope evidence of a vapor-dominated system.

Opal, which is found at the base and in large joints in the latites, exhibits fumarolic texture. This texture, along with evidence of bleaching of the latites, suggests a mechanism whereby as the fluids approached the base of the latites and fluid pressure was released, boiling ensued and opal precipitated. This process also limits alteration to the latites. It is also

possible that the latites formed a relatively impermeable cap on the system and that the opal represents a zone of cooling/condensation, also limiting the extent of alteration of the latite units. The distribution of the opal indicates fluids reached the base of the latite along the same linear zones the latites themselves travelled, because the amount of opaline material tends to decrease outward from the vent areas.

CONCLUSIONS

This study of the Alum Mountain geothermal system was suspended in 1977 because of logistical and instrumental problems. A partially completed geologic map (not included with this report), several oxygen isotope analyses, preliminary clay separates, and x-ray studies of a new zeolite mineral were products of this study. Renewed activities on the part of the investigators (Landis and Northrop, U. S. Geological Survey, Denver, Colorado) have produced additional geological mapping and trace element analyses. As an ongoing study, Alum Mountain provides unique opportunities to learn about the three-dimensional aspects of vapor-dominated acid sulfate springs (geothermal systems). Appropriate U.S.G.S. and New Mexico State officials will receive any reports or publications that arise from this work.

Truth or Consequences Area

GEOLOGY

Eastern Engle Basin

Summary. This area (Figure 59) overlaps the southern Rio Grande rift and its eastern marginal uplift, the Fra Cristobal Mountains. The Hot Springs and Walnut Canyon faults separate the two domains. The Engle basin is filled with a large thickness of sediments equivalent to the late Tertiary and Quaternary Santa Fe Group, as described in the Espanola basin 300 km north by Galusha and Blick (1971). The Fra Cristobal uplift, exposing Precambrian basement and sedimentary rocks from Cambrian through Permian age, dies out southward into the Cutter sag in which Permian, Cretaceous and early Tertiary rocks crop out. The Cutter sag is a marginal uplift separating the structurally higher Fra Cristobal and Caballo uplifts to the north and south, respectively; it extends westward from the Jornada del Muerto basin. The Jornada del Muerto basin, an elongate synclinal basin, borders the uplifts to the east. It is filled with relatively thin bolson deposits overlying Mesozoic and early Tertiary rocks and is probably a Laramide feature unrelated to the Rio Grande rift. Laramide deformational features are present in the Caballo uplift to the south (Kelley and Silver, 1952; Mason, 1976) and the Fra Cristobal uplift (Kelley and McCleary, 1960; McCleary, 1960; Warren, 1978).

Three stratigraphic and structural domains are present within the eastern Engle Basin. Paleozoic sedimentary rocks overlying Precambrian basement are exposed in the Fra Cristobal uplift, Cretaceous rocks are exposed in the Cutter sag to the south, and Quaternary volcanic units are found in piedmont gravels within the Engle basin. For details of stratigraphy, see Warren (1978; Appendix 2, this report).

Figure 59. Sketch map of the principal physiographic features in south-central New Mexico. Truth or Consequences study area outlined in bold lines.

The Hot Springs fault does not bound the Fra Cristobal uplift as previously thought, but continues northward from Black Bluffs. Another fault 1.5 km east, the Walnut Canyon fault, bounds the Fra Cristobal uplift. Post-basalt movement (90 m) has occurred along the Hot Springs fault in the Black Bluffs area. Farther north, this movement is divided between the Hot Springs and Walnut Canyon faults. The Hellion monocline, a Laramide structural element overlooked in previous work, is found within the Fra Cristobal uplift. Folds of probable Laramide age are present within the Cutter sag.

The geometry and kinematics of four major faults associated with the Rio Grande rift have been established (Figure 60). Three of these faults, the Hot Springs, Walnut Canyon and Massacre Gap faults, separate the three structural domains within the study area, the Engle basin, Fra Cristobal uplift and Cutter sag. Rotational movement, hinging to the north, has occurred along the Double Peak fault. Strike-slip movement cannot be significant along either the Double Peak or Walnut Canyon faults, since such movement would disrupt the coherent block forming the Cutter sag to the south. Gravity sliding, resulting from topographic elevation of the Fra Cristobal uplift and Cutter sag, post-dates (i.e., covers) the Double Peak fault.

Movement along the Hot Springs fault in the Black Bluffs area has dropped volcanic units 90 m to the west. North of the Massacre Gap fault, this displacement decreases to 60 m and is divided between the Hot Springs fault (30 m) and the Walnut Canyon fault (30 m) to the east. Post-basalt displacement along the Hot Springs fault completely disappears farther north.

Basalts within the area and their inclusions were investigated by detailed petrography, wet chemical analyses and microprobe analysis of individual mineral phases (Warren, 1978; Appendix 2, this report; Warren and others, 1979). Basalts form two suites: an earlier Mitchell Point suite with tholeiitic

Figure 60. Geometric arrangement of high-angle normal faults separating the three structural elements of the T. or C. area, Fra Cristobal Range(FCR), Engle basin, and Cutter sag. DD' = Double Peak fault, WW' =Walnut Canyon fault, HH' = Hot Springs fault, MM' = Massacre Gap fault.

affinities and a later Fra Cristobal suite which is alkalic. Six maars are present; they generally preceded basalt eruptions.

Inclusions of lherzolite, pyroxenite and granulite are found within all Fra Cristobal basalts. Mantle temperatures were calculated from the chemical compositions of the inclusions and pressure limits for their stability obtained by comparison with phase relationships. This yielded a best-fit geotherm of $31^{\circ}\text{C}/\text{km}$ and a Moho depth of about 31 km (Warren and others, 1979). Megacrysts of clinopyroxene, olivine, anorthoclase, pleonaste and titanomagnetite, found within the Fra Cristobal basalts, are also thought to exist within a layer between 28 and 35 km depth containing the pyroxenites and granulites. Lherzolite is present at depths exceeding 35 km.

Geothermal potential. Surface manifestations of geothermal activity in the Engle basin indicate a low geothermal potential. Hot springs near Truth or Consequences are cool (37° to 46°C), and the waters are high in NaCl, indicative of a hot-water rather than a vapor-dominated system. However, the high fossil temperatures (90° to 170°C) obtained by the Na-K-Ca geothermometer (R.E. Zilinski, Jr., personal communication, 1976; see also Appendix 7, this report) for these springs, the relatively high geothermal gradient of over $30^{\circ}\text{C}/\text{km}$ calculated in this study, and the extensive Pleistocene tectonism and volcanism, suggest a higher geothermal potential for the area than is indicated by surface activity.

Truth or Consequences

Summary. Late Cenozoic extensional tectonics, basaltic volcanism and thermal activity characterize the area near Truth or Consequences. Major structural features within this part of the Rio Grande rift (Kelley, 1952; Woodward and others, 1978) include the Caballo, Fra Cristobal and Mud Springs uplifts; the

Cutter Sag; and the Engle, Palomas and Jornada del Muerto basins (Figure 59). The uplifts are tilted fault blocks revealing complex internal geometry and well-exposed sections of Precambrian and Paleozoic rocks. The western part of the area includes parts of the Engle and Palomas basins which are separated by the Mud Springs uplift and which consist of grabens within the Rio Grande rift (Woodward and others, 1978).

Precambrian igneous and metamorphic rocks, together with Paleozoic formations (chiefly marine) are well-exposed in the Caballo uplift in the southern part of the area. Extensive outcrops of Late Cretaceous strata (Mesaverde Group and McRae Formation), with a cumulative thickness of 2200 m, crop out over much of the eastern and southern parts of the area. Cenozoic units include both igneous and sedimentary lithologies broadly distributed throughout the area. For details on stratigraphy, see Loeber (1976a; Appendix 2, this report).

Two distinct periods of Late Cenozoic volcanism can be distinguished in this area. The first is characterized by andesitic dikes, and the second by Pleistocene basalt flows and cones. Based on 14 new whole-rock chemical analyses, the basalts are alkali olivine in composition (Loeber, Appendix 2) and contain distinctive suites of spinel lherzolite xenoliths and xenocrysts of Al-rich augite and oligoclase.

Evidence of explosive volcanism is preserved as four previously unrecognized maars along the margins of Elephant Butte Reservoir. Dissected craters less than 1 km in diameter are bounded by low rims of pyroclastic material which are locally intruded by alkali basalts. Paleospring deposits, another manifestation of volcanism in the area, include travertine, manganese-oxide and hydrothermal alteration products.

Extensional tectonic features related to the Rio Grande rift are widespread throughout the area. Northeast-trending normal faults, down-dropped to the west, are characteristic.

The geology of the south and east end of Elephant Butte reservoir has been studied by Loeber (Appendix 2). The main rift-bounding fault, the Hot Springs fault, has been active volcanically and geothermally until very recently (Loeber, 1976b). Rift-related faults have served as conduits for basalt flows and maar eruptions. Although the dominant volcanic rocks are alkali basalts, hypersthene-and quartz-normative basalts also have been found. Phreatomagmatic eruptions produced at least 10 maar craters, some of which were centers for hot spring activity.

Mapping to the north and east end of the reservoir (Figure 61) indicates that extensive phreatomagmatic eruptions also have occurred in Quaternary times in this area. An older maar deposit is overlain by lava flows which are covered by two maar deposits. Each maar deposit covers an area of over 50 to 75 km² with thicknesses up to 18 m. At least two large maar craters have been the site of siliceous hot spring activity which deposited extensive opal (up to 10 m thick locally). Late-stage hydrothermal activity in the maar craters has been restricted to travertine and manganese deposition.

Inclusions of lherzolites, websterites, two-pyroxene granulites and megacrysts of olivine, clinopyroxene and spinel have been found at various alkali basalt centers. Using the geothermometer of Wood and Banno (1973), temperatures of equilibration of coexisting pyroxenes in lherzolites, websterites and granulites have been obtained. Since there is very little evidence for equilibration between the basaltic host and the inclusions except for thin reaction zones at the contacts, these temperatures probably represent the temperatures of the rocks at the time the basalts tore them from the walls.

Scale 1:62,500

SYMBOLS

- Contact, dashed where approximately located.
- +--- Fold Axes { antiform, showing direction of plunge.
syncline, showing direction of plunge.
- Fault, dashed where covered. (all faults are high-angle normal faults)
Dot on downthrown side.
- Water

PRELIMINARY GEOLOGIC MAP OF THE TRUTH OR CONSEQUENCES-ENGLE AREA, SIERRA COUNTY, NEW MEXICO

(overlaid to accompany Engle, New Mexico U.S.G.S. 15' Quadrangle)
(compiled from geologic mapping at scale of 1:12,000)

GEOLOGY AND COMPILATION BY
A.M. Kudo and K.N. Leober
December, 1975

ROCK UNITS

- Qs Hot spring deposits, including travertine, manganese. (Quaternary)
- Qp Pediment gravels. (Quaternary)
- Qtsf Santa Fe Group, unconsolidated sediments filling graben. (Quaternary-Tertiary)
- Ku Cretaceous undifferentiated { includes Hutton Fm., Mesaverde Gp.,
Mancos Shale, Dakota Sandstone.
- Pa Paleozoic undifferentiated { includes Permian through Carboniferous
sedimentary units.

IGNEOUS ROCKS

- Qm Quaternary dissected volcanic mass.
- Qb Quaternary basalt flows.
- Qba Quaternary basalt cone.
- Qib Quaternary intrusive basalt plug.
- Tid Tertiary trachy-andesitic dikes.
- Kib Cretaceous intrusive breccia (intermediate composition).
- PC Precambrian igneous and metamorphic crystalline rocks.

Figure 61a. Preliminary geologic map of the Truth or Consequences-Engle area, New Mexico.

Figure 61b. Geologic sketch map of the area northeast of Elephant Butte Reservoir.

Since alkali basalt magmas were hotter than the country rock, any approach to equilibrium would drive the temperatures higher; hence, these temperatures would serve as minimum temperatures. In conjunction with experimental data from Irving (1974), Kushiro and Yoder (1966) and MacGregor (1970), these temperatures were used to obtain stability ranges of the observed crystalline phases in terms of pressure (Figure 62). For a given temperature, certain mineral assemblages will be stable over a wide pressure range, but for a few of the inclusions the pressure range is small. Hence, the geotherm can be positioned quite accurately. The best estimate for the Truth or Consequences area is about $31^{\circ}\text{C}/\text{km}$, corresponding to a heat flow of 2.3 HFU according to the model of Decker and Smithson (1975).

Because the petrologic data suggest that the inclusion suite is not cognate to the basaltic host, but instead represents samples of wall-rock torn from the conduits, the pressure-temperature estimates can be used to reconstruct the positions of the various rock types at depth. This reconstruction suggests that granulites with densities close to 3.0 g/cm^3 are positioned at depths above 31 km and the websterite and lherzolites with densities close to 3.3, below 31 km (Figure 63). It is likely that the granulite-websterite contact represents the Moho and that the upper mantle may be layered such that lherzolite lies below websterite at a depth close to 35 km. This indirect evidence is consistent with the geophysical determination of the depth to the Moho in the rift (Olsen and others, 1977; McCullar and Smithson, 1977).

Geothermal potential. The Truth or Consequences thermal area occurs on the west side of the Rio Grande near the center of the city. Shallow (less than 30 m) wells and springs discharge thermal waters ranging in temperature from 37°C to 46°C . Chemical characteristics of the waters have been compiled by Summers

Figure 62 . Calculated temperature and pressure ranges for the inclusion suite of granulites (G), websterites (W), and lherzolites (L) found in the alkali basalts of the T. or C. area. The upper dashed line is for a heat flow of 2.4 HFU and the lower for 2.1 HFU according to model by Decker and Smithson (1975). Best fit would be a heat flow of 2.3 HFU corresponding to a geothermal gradient of about $31^{\circ}\text{C}/\text{km}$. See text for further explanation.

Figure 63. Inferred petrology of the lower crust and upper mantle based on stability estimates of the inclusions suite. Symbols are: A = anorthoclase megacrysts, G = granulites, Q = quartz-bearing granulites, W = websterites, M = megacrysts of olivine, clinopyroxene, or pleonaste, L = lherzolites, ρ = density in g/cc. The megacrysts' position was established by chemistry only.

(1976, 1965a, b). Yearly sampling indicates that the water maintains a fairly uniform composition, in addition to other parameters such as pH and temperature.

Hydrologic investigations of the thermal waters have been made in the past by Powell (1929), Theis and others (1941), and Kelley and Silver (1952). They reported that some mixing takes place between thermal and nonthermal waters, but essentially they are different based on chemical compositions. The water issues from fractured Pennsylvanian limestone into overlying alluvium. The aquifer is considered to be the limestone with recharge from the Rio Grande. Various heat sources have been proposed, but with the occurrences of Pleistocene basalts in the local area, it seems reasonable to postulate a basaltic intrusion at depth for the heat source. The chemistry of the water (high NaCl) is indicative of hot-water systems rather than vapor-dominated systems.

Elsewhere geothermal waters have been used for a variety of purposes, including electrical power generation, space heating and agricultural applications. In Truth or Consequences, the thermal waters are the basis for bath houses and to some extent tourism. Reservoir temperature calculations based on the silica and Na-K-Ca geothermometer give temperatures ranging from 90 to 180°C (Table 4). These values are at or below the 180°C currently required for electrical generation from flashed steam. Electric power generation from geothermal resources in Truth or Consequences also appears to be limited by the small volumes of water involved in the system. Space-heating applications generally require surface temperatures above 50°C. Some wells in the area may barely satisfy these requirements. Agricultural uses include greenhouses and hydroponics. Once again the waters of Truth or Consequences are not warm enough (generally require 80-90°C at the surface).

The surface manifestations of the geothermal potential of the Truth or Consequences are poor. No obvious geothermal prospect was found. However, recent fault-controlled volcanism, the relatively high geothermal gradient (over $30^{\circ}\text{C}/\text{km}$) calculated from petrology, moderately high geochemical reservoir temperatures, and water mixing models (Table 4) suggest the potential for geothermal resources in the area is better than is manifested at the surface. More work, perhaps resistivity surveys, is warranted before firm conclusions about the geothermal potential of this area are made.

GEOPHYSICS

Introduction

A gravity survey was conducted in the Truth or Consequences-Engle area to aid in determining structural relationships and to investigate anomalies that might be related to geothermal activity. A simple Bouguer Gravity map (Figure 64) was compiled from the data and used for interpretation.

Data

Gravity measurements were taken at 80 stations distributed across the area. Station location was planned to provide coverage perpendicular to the trends of the major structures. This resulted in a northeasterly traverse across the Palomas basin-Mud Springs uplift-Engle basin and a northwesterly traverse across the Hot Springs fault. Measurements were taken at points of known elevation such as benchmarks, section corners and landmarks identified on topographic maps. Elevations for five points on the east side of the Hot Springs fault (along Y-Y') were determined using a portable altimeter-recording barograph system.

The base station was located at the Post Office in Truth or Consequences, which is an official Gravity Base Station of the World Relative Gravity Reference Network (Defense Mapping Agency, 1974).

A Worden Pioneer gravimeter (#552 from the University of New Mexico) was used for all measurements.

Values of observed gravity were reduced to free air and simple Bouguer anomalies using a computer program on file at the University of New Mexico. Terrain corrections were not made, since they would have little effect on the

SIMPLE BOUGUER GRAVITY MAP

Truth or Consequences-Engle Area
R. L. LOEBER, 1974

Contour interval: solid lines = 5 mgals
dashed lines = 1 mgal

Notes: Gravity measurements tied to Gravity Base
Station of World Reference Network
(Defense Mapping Agency, 1974)

Number of data points = 80

Symbols:

- gravity station location
- section lines
- (-) (+) a relative gravity 'low' (-) or 'high' (+)
- area of geologic map
- location of active hot springs
- trace of normal fault, relative movement indicated

Figure 64. Simple Bouguer gravity map of Truth or Consequences-Engle area (from Loebler, Appendix 2, this report). See Figures 65 and 66 for cross sections.

reduced data (terrain corrections were less than 1 mGal for all stations).

Interpretation

Simple Bouguer values were plotted and contoured to produce the simple Bouguer gravity map (Figure 64). Values range from -160 to -195 mGals in the area. The Engle and Palomas basins are defined by large negative anomalies (-195 mGals), while the uplifted eastern side of the Hot Springs fault and the Mud Springs uplift (continuing into Truth or Consequences) are characterized by less negative anomalies (about -160 mGals). Steep gradients occur along parts of the Mud Springs and Hot Springs faults. Active hot springs are associated with the southeastern extension of the Mud Springs uplift.

Modeling

Residual gravity profiles were constructed across major structures along the lines X-X' and Y-Y' (Figures 65 and 66). These were obtained by subtracting the regional gradient (from Woollard and Rose, 1963) from the simple Bouguer values.

Theoretical gravity values for subsurface models based on geologic constraints were calculated with the aid of a computer program. The theoretical values were compared to the observed values, and changes were made to the subsurface model until the theoretical values approximated the observed values. Interpretations were then based on the best-fitting model.

The computer program used was based on Program D2GF from Parasnis (1973), which calculates the gravity anomaly of a two-dimensional feature of arbitrary, uniform cross-section. The geologic model is approximated using n-sided polygons of various density contrasts. Density contrasts were based on rock densities from Sanford (1968).

Figure 65. Residual gravity profile along X-X', Figure 64, Truth or Consequences area (from Loeber, Appendix 2, this report).

Figure 66. Residual gravity profile along Y-Y', Figure 64, Truth or Consequences area (from Loeber, Appendix 2, this report).

Subsurface models for theoretical calculations are based on all available geologic information. In extrapolating surface data to depth, an important variable to consider is the thickness of each unit. Variations in thickness can result in lateral changes in mass which will affect the gravity. Table 14 summarizes the densities and thicknesses used in the models.

Conclusions

Gravity profile X-X' (Figure 65).

1. Assuming a complete Cambrian through Tertiary section, the northern Palomas basin is 3000 m deep to the Precambrian and contains a minimum of 350 m of Santa Fe strata.
2. The Mud Springs fault may actually be a series of en echelon normal faults, down-dropped to the southwest. A single fault-plane model produces a gradient much steeper than that observed; several down-dropped blocks are hypothesized to lower the gradient, but leave unchanged the overall anomaly. Total displacement on this series of faults is about 3000 m.
3. The Mud Springs uplift is a northeast-dipping fault block. In a regional sense it forms the southwestern limb of a large syncline that continues north to the Engle basin. Small displacement faults may occur between the Mud Springs uplift and the Engle basin, but no single major displacement is indicated by the gravity data. The preferred interpretation involves gently dipping units plunging into the Engle basin.
4. Stratigraphic separation on the Hot Springs fault probably increases to the north, since units dip northward into the Engle basin.
5. The Santa Fe Group has minimum thickness of 1050 m in the southern part of the Engle basin. It is likely that this thickness is greater, since

Symbol	Unit Name	(g/cm ³) Density	Thickness (feet)	
			for Y-Y' section	for southern part of X-X' section
QTsf	Santa Fe	2.1	unknown	unknown
Tt	Thurman	2.3	0	1000-2000
Tp	Palm Park	2.3	0	500-1000
TKm	McRae	2.35	3200	0
Kmv	Mesaverde	2.35	3300	1000-3000
Km	Mancos	2.35	330	330
Kd	Dakota	2.35	190	190
Psa	San Andres	2.54	760	760
Py	Yeso	2.54	620	620
Pa	Abo	2.54	560	560
Pm	Magdalena	2.60	1100	1100
Om	Montoya	2.60	350	350
Oo	El Paso	2.60	390	400
Gb	Bliss	2.60	130	130
p6	Precambrian	2.67	--	--

Table 14. Summary of formational thicknesses and densities in various areas. Subsurface models are based on these data (from Loeher, Appendix 2, this report).

many of the Tertiary through Cambrian units thin to the north and northwest from the vicinity of the Caballo uplift.

Gravity profile Y-Y' (Figure 66).

1. The west side of this profile must conform to the northern section of the X-X' profile. The chief feature is the minimum thickness of the Santa Fe Group, about 1050 m. The top of the Precambrian is at about 4400 m below the surface.
2. The trace of the Hot Springs fault corresponds to a steep gravity gradient, and the model suggests a single fault plane.
3. The uplifted eastern flank of the rift is east of the Hot Springs fault. Minimum displacement at this point on the Hot Springs fault is 1000 m.

CONCLUSIONS

Surface manifestations of geothermal activity in the Engle basin and Truth or Consequences area indicate a low geothermal potential. However, Na-K-Ca geothermometry, moderate geothermal gradient ($31^{\circ}\text{C}/\text{km}$, determined by petrology) and Pleistocene tectonism and volcanism suggest a potentially more significant geothermal anomaly. The sources of heat for hot springs at Truth or Consequences are probably young basalt intrusions at depth. Spring activity and volcanism are mainly fault-controlled. More work, particularly geoelectric studies, is warranted before firm conclusions can be drawn about reservoir size, heat content and the significance of the geothermal resource in this area.

Albuquerque Basin

GEOLOGY

General

The Albuquerque basin is one of the largest of several north-trending, en echelon grabens or half-grabens of Neogene age which form the Rio Grande rift (Callender and others, 1976; Kelley and others, 1976). The basin has been mapped and discussed in detail by Kelley (1977). Although close to a major population center, and therefore potentially ripe for geothermal exploitation, the Albuquerque basin displays relatively few indications of significant geothermal potential, mainly young volcanic rocks and Plio-Pleistocene spring deposits. In this project geologic research concentrated on areas with these features.

Specific Studies

Mapping and petrologic studies of Quaternary volcanic features are discussed in Kelley and Kudo (1978). Preliminary Sr-isotope data were given earlier in this report. K-Ar ages are reported by Kudo and others (1977), Bachman and Mehnert (1978) and Kelley and Kudo (1978). The youngest volcanic activity in the Albuquerque basin took place in the Cat Hills volcanic field (basaltic) about 140,000 years ago. Most magmatic centers are likely to be deeper than 24 km, which precludes their development for geothermal energy. However, andesitic centers at Los Lunas, Torre Hill and Black Butte were generated at shallow crustal levels and may have acted as heat sources (Kasten, 1977; Appendix 2, this report). Detailed discussions of the geology and petrology of volcanic rocks of the Albuquerque basin will be found in Aubele (1978; Appendix 2, this report), Aubele and others (1976), Aubele (1979),

Kasten (Appendix 2), Kasten and others (1976), Aoki and Kudo (1976), Zimmerman (1979; Appendix 2, this report), and Zimmerman and Kudo (1979a, b).

Alignment of volcanic centers parallel to the rift boundaries and intrabasin horsts, and volcanism that has been active for over two million years and continues to be so, suggest the possibility of additional heat sources at shallow depths in the crust, particularly near young volcanic centers such as Cat Hills, Wind Mesa and the Albuquerque volcanoes. No active hot springs are known, but geothermal waters may be present at depth, in and below the Santa Fe Group.

The western border of the basin contains ample evidence of a "fossil" geothermal system less than two million years old along the Lucero uplift. Detailed geologic mapping has established at least four periods of hot and cold-spring activity, and the geometry of the local geothermal "plumbing" system is locally visible (Zilinski, 1976 and Appendix 2; Callender and Zilinski, 1976; Kelley and others, 1976). Trainer and Lyford (1979) consider springs and spring deposits along the Lucero uplift to be derived from a complex intermixing of underground water from the San Juan Basin, local recharge and deep geothermal water. Detailed gravity analysis (Ander, 1980) suggests the presence of a large, upper crustal intrusive of Neogene age in this area.

ELECTRICAL STUDIES

Rio Rancho

Introduction. Results of the electrical resistivity tests in the Rio Rancho area of the Albuquerque basin have been reported by Jiracek and others (1976) and in more detail by Smith (1977 and Appendix 2). The survey consisted of a combined asymmetric Schlumberger and equatorial bipole-dipole sounding together

with two bipole-dipole mapping studies (Table 8). The tests centered about Shell Oil Company's abandoned Santa Fe Pacific No. 1 wildcat well (Figure 67). As mentioned earlier, the Rio Rancho tests were made as a field trail in a part of the Rio Grande rift and were selected for convenience rather than specific geothermal promise.

Direct current mapping. Two bipole-dipole, total-field, apparent resistivity maps of the Rio Rancho Estates area using approximately 2-km long bipoles are shown in Figures 68 and 69. The near-symmetry about the bipoles in each map is indicative of quasilateral electrical homogeneity in the survey area.

Variations from symmetry are probably related to porosity, salinity and clay content in the Santa Fe Group aquifer; it is unlikely that basement in excess of 3 km depth is detected in the areal extent of the maps. The numerical values of the measured apparent resistivities are discussed in the sounding section which follows. The total field maps demonstrate a clear compatibility with the sounding results. However, the area is admittedly less complex than expected in most geothermal prospects.

Direct current sounding. Results of the sounding are shown in Figure 70, where asymmetric Schlumberger results from the east-west bipole (Figure 69) are combined with corresponding equatorial measurements out to an effective spacing of 6 km to the north. Included in Figure 70 is a calculated sounding curve for the interpreted six-layered model obtained by inversion (Zohdy, 1973a; Inman and others, 1973). Deviation from the observed curve in the vicinity of 2-km spacing is undoubtedly due to lateral resistivity variations not considered in the layered inversion routines. Nevertheless, comparison between the sounding and drillhole results is very encouraging. The interpreted depth to the resistive basement (3210 m) compares favorably to the encountered depth of the

Figure 67. Location of Rio Rancho Estates study area.

Figure 68. Total field apparent resistivity map of Rio Rancho study area derived from north-south transmitter.

Figure 69. Total field apparent resistivity map of Rio Rancho study area derived from east-west transmitter.

Figure 70. Combined asymmetric Schlumberger and equatorial bipole-dipole sounding at Rio Rancho study area and interpreted seven-layer model.

crystalline Precambrian basement (3330 m). There is also an almost one-to-one correspondence of the 25 ohm-m, 300-m thick layer and underlying 7 ohm-m zone with the fresh, potable/saline aquifer interpreted in the well by Hiss and others (1975). Thus, the sounding appears to accurately estimate the extent of the fresh water zone and the depth to the saline interface. Using empirical relations, Smith (1977 and Appendix 2) attempted to use the sounding interpretations to quantitatively estimate water quality; the unsatisfactory correlation with measured salinities is probably related to clay effects. Our first deep electrical sounding in the Rio Grande rift, therefore, produced encouraging, positive correlations but also cautioned against overconfidence in inferring detailed hydrologic conditions.

COCORP Area

Introduction. The first high resolution seismic information regarding the deep basement rocks of the crust and upper mantle of the Rio Grande rift was collected in 1975 by the Consortium for Continental Reflection Profiling (COCORP) (Oliver and Kaufman, 1976; Brown and others, 1979). These initial vibroseis sounding lines (28.7 and 9.4 km long) are designated 1 and 2, respectively, in Figure 71. The most prominent event recorded, even on field monitors, was a reflection "bright spot" which correlated with a proposed 18-km deep magma chamber detected nearby using microearthquakes (Sanford and others, 1973). Following the 1975 success, the COCORP group returned in 1977 to complete 127 km of additional soundings, lines 1A, 2A, 3 and 4 of Figure 71 (Brown and others, 1977). Using these results and additional microseismic analysis, Sanford and others (1977) have determined the areal extent of the suspected magma body to be $\sim 1700 \text{ km}^2$ as indicated in Figure 71. The microearthquake results are also considered to have detected smaller, shallower

Figure 71. COCORP study area in New Mexico. Location of Figure 72 in box.

(~4 km) elongate molten plutons near Socorro (Figure 71), although COCORP processing to date (S. Kaufman, personal communication, 1978) has not revealed the bodies.

As one might expect, the region has been marked by high thermal gradients, exceeding $150^{\circ}\text{C}/\text{km}$ near Socorro, with corresponding values of heat flow greater than 400 mWm^{-2} (10 HFU) (Reiter and Smith, 1977). These measurements resulted in over 360 km^2 surrounding Socorro being designated Socorro Peak KGRA. Unfortunately, there is no published thermal gradient information elsewhere in the vicinity; however, a re-leveling survey (Reilinger and Oliver, 1976) has recorded maximum uplift of 20 cm about 25 km north of Socorro. The re-leveling result collected over a 40 year period, is "one of the most clear-cut and striking anomalies of this scale ever detected by leveling in the United States." Thus, the combined geophysical data in this area, which has the highest seismicity in New Mexico (Sanford and others, 1972), together with the geologic investigations (Chapin and Seager, 1975), identify one of the most active parts of the Rio Grande rift.

Electrical studies in the COCORP area have combined shallow direct current resistivity investigations with deep probing magnetotelluric soundings. Eight MT sites were occupied along COCORP lines 1, 1A, 2 and 2A; the resistivity study area centered about MT station 8 (Figure 71). Preliminary results from these investigations were presented by Jiracek and others (1977). The data are still being processed and interpreted; therefore this report presents preliminary results only.

Direct current mapping and sounding. To "shakedown" equipment and to provide shallow control for the MT soundings, a brief direct current resistivity survey was run near MT site 8 (Figures 71 and 72). The area lies in part of the

Figure 72. Location of stations for electrical studies in Seville National Wildlife Refuge (geology after Woodward, Callender and Zilinski, 1975). See text for explanation of symbols.

Sevilleta National Wildlife Refuge on the eastern edge of the Rio Grande rift (Figure 72). Faults and rock units marked in Figure 72 are reproduced from Woodward, Callender and Zilinski (1975). The units contemporaneous with rifting are: 1) i-intermediate volcanics, 2) b-basalts, and 3) s-sedimentary rift fill. Pre-rifting rocks are represented by volcanic rocks (v), Precambrian granite (a) and sedimentary rocks (sr). As shown in the figure, two orthogonal, nearly 2-km long bipole transmitters were occupied and used for limited bipole-dipole mapping with emphasis on equatorial sounding points. A short-spread Schlumberger sounding was centered at the common bipole electrode and expanded along the axis of the N-S bipole. Asymmetric Schlumberger soundings were made along the E-W bipole.

The symmetric and asymmetric Schlumberger soundings, together with the four equatorial bipole-dipole soundings are combined in Figure 73; e.g., E and W refer to equatorial soundings directed east and west, respectively, along the perpendicular bisector of the N-S bipole (Figure 72). Variations in the four equatorial segments testify to the geologic units mapped in Figure 72. The highly resistive portion of the W curve clearly marks the intrarift horst block exposed as the small granitic outcrop (a) on the left of Figure 72. Curves E, N and S sound the shallow basement beneath the graben fill; however, results are affected by the Los Pinos Mountains, basin structure and exposed pre-rifting sedimentary rocks (sr), respectively (Figure 72). Considering these lateral complexities, one-dimensional interpretations of the soundings are improper. The north and east curves are least influenced by lateral variations and yield one-dimensional interpretations (Zohdy, 1973b) which are considered useful. The generalized geoelectric sections interpreted for these curves are given in Figure 73. The models are considered to set a reasonable depth estimate to the bottom of partially water-saturated graben fill, about 400-500 m.

Figure 73. Combined symmetric and asymmetric Schlumberger and equatorial bipole-dipole soundings in Sevilleta National Wildlife Refuge study area. Generalized four-layer models interpreted using north and east equatorial segments.

Magnetotelluric sounding. Eight magnetotelluric soundings were made in 1977 along COCORP lines 1, 1A, 2 and 2A (Figure 71). The investigations were performed as a cooperative study with the California Institute of Technology. Two electric and three magnetic field components were recorded over five overlapping frequency bands using a three-component cryogenic magnetometer. Due to an electronic difficulty, vertical magnetic fields (H_z) were not measured at three of the MT sites. All data were digitally recorded and covered a period range of 0.01 to 1000 seconds.

Data processing has thus far proceeded in a fashion described by Reddy and Rankin (1974). The fast Fourier transform was used to obtain frequency domain estimates of the tangential electric and magnetic fields for calculation of the tensor impedances. The auto- and cross-power spectral estimates were rotated in 5 degree steps for each period band to determine the principal impedance directions (Sims and Bostick, 1969). For a strictly two-dimensional earth, one of the principal directions of rotation corresponds to the structural strike direction, the other, perpendicular to it, equals the dip direction. The two directions give rise to different values of apparent resistivity (Stanley and others, 1977) simply designated $p_{\max}$ and $p_{\min}$; $p_{\max}$ and $p_{\min}$ are identical for one-dimensional structures. The apparent resistivity in the strike direction, the so-called transverse electric (TE) mode, can be distinguished from the dip direction, transverse magnetic (TM), by consideration of the vertical magnetic field. Where H_z is available, the dip direction is given by the horizontal direction in which the magnetic field is most highly coherent with H_z . As this correlation may be a function of frequency (i.e., structural trends may vary with depth), the strike direction need not simply correspond to $p_{\max}$ (or $p_{\min}$) over the entire spectrum. In the absence of the H_z component, a combined knowledge of geology and MT response behavior has been used to best separate

the strike and dip directions.

Figure 74 presents computed values of $p_{\max}$ and $p_{\min}$ together with the azimuth angle of tensor rotation corresponding to the principal strike direction at station 6 (Figures 71 and 72). To assure a high degree of signal-to-noise, only points with multiple coherences (Reddy and Rankin, 1974) greater than 0.7 are plotted. The results plotted for station 6 represent the preliminary processing to date. We expect considerable improvement in our final overall results by the application of new averaging and noise reduction procedures currently being implemented (Reddy and others, 1976; Goubau and others, 1977). However, even at this stage of processing, there are obvious conclusions which can be drawn from the results. The apparent resistivity curves at station 6 clearly indicate shallow and deep conductive zones (~ 10 ohm-m) separated by a resistive intermediate region. Also, the strike direction sensed over four frequency decades is rather consistently 45° to the northeast. To quantify the depth information, we have hand-smoothed the sounding results from each station and performed a one-dimensional inversion on the TE curves. Such inversion of the TE mode is thought to more nearly approximate the true vertical resistivity distribution. Two-dimensional MT modeling to date (Jupp and Vozoff, 1977; Vozoff, personal communication, 1978) has exposed serious limitations to this procedure for complex structures. Consequently, we must be prepared for significant modifications to our results upon further processing and two-dimensional modeling.

Figure 75 presents a geoelectric section prepared by joining the one-dimensional inversions for MT sites 1-7 (Figure 71). The inversion scheme developed by Bostick (1977) has been used. Taken at face value the section illustrates some expected features but also some rather surprising results. The Los Pinos and Manzano Mountains bounding the rift on the east are revealed

Figure 74. Apparent resistivity values of ρ_{max} and ρ_{min} together with principal strike directions versus period at MT station number 6.

Figure 75. Geoelectric section along COCORP lines 2 and 2A obtained by one-dimensional magnetotelluric inversion.

as expected by a resistive block under station 7. Station 5 detects an intrarift horst block, probably an extension of the granite surface exposure mapped in Figure 72. Its extension to the north under station 5 has been independently confirmed by the COCORP results (Oliver and Kaufman, 1976) and, therefore, some modification of the faults inferred in Figure 72 is required. Near-surface conductive material (<50 ohm-m) beneath all other MT sites may be identified with rift fill having varying amounts of water saturation. Such a correspondence yields a reasonable estimate of its thickness (~ 2 km) at station 6, noticeably deeper than MT or VES results at station 8 farther south, but excessive depth (~ 5 km or more) at stations to the west. Probably a more surprising result, however, is the pervasive conductive zone (<10 ohm-m) computed for all stations at depths as shallow as 6 km (Station 4) beneath the resistive (>50 ohm-m) basement. At depths on the order of 18 km it might be associated with the proposed magma layer. MT results depicted in Figure 75, however, suggest a conductive zone under all sites, with kilometers of relief and thickness. Given the assumptions and preliminary nature of our interpretation, we must withhold final comments on these findings (see Jiracek and others, 1979). The very shallow depth to the conductive zone in the center of Figure 75 may be an artifact of one-dimensional inversion. We consider conclusive understanding of such MT data to be of utmost importance in regional geothermal evaluation of the Rio Grande rift. The actual nature of crustal conductive zones in geothermal regions has been the source of some mystery; Stanley and others (1977) have emphasized the importance of pore water and alteration products in the deep crustal thermal environment.

To investigate the gross structural grain of the basement rocks in the vicinity of the MT sites, the MT strike directions measured in the 100-sec period band are presented in Figure 71. The results align with the north-south

trend of the rift except at stations 4, 5, 6 and 8, where considerable oblique structure is evident. This cross structure agrees with the geologic mapping (Figure 72) and may represent a separate structural episode. For additional data on the COCORP area, see Jiracek and others (1979).

CONCLUSIONS

Geologic and petrologic studies suggest the Albuquerque basin has low geothermal potential, although local thermal anomalies may exist near young volcanic centers such as the Albuquerque volcanos, or at the southwestern edge of the basin (Lucero uplift). Additional heat-flow measurements and detailed geophysical studies should be carried out west of Albuquerque to delineate potential low-temperature geothermal reservoirs. Detailed geophysical work in the Albuquerque basin was done to calibrate geoelectric techniques and to explore deep sources of thermal energy. This work suggests the southern end of the basin has greater geothermal potential caused by a crustal magma body less than 20 km below the surface.

San Ysidro - Jemez Area

GEOLOGY

The western margin of the Rio Grande rift between San Ysidro and Coyote has been mapped at 1:24,000 scale; three maps, the San Ysidro, Gilman and Jarosa quadrangles (Woodward and Ruetschilling, 1976; Woodward and others, 1977, Woodward and Timmer, 1979, respectively) have been published by the New Mexico Bureau of Mines and Mineral Resources. Previous work on the area (Woodward and Martinez, 1974) also delineates evidence of young faulting and hydrothermal activity associated with the Rio Grande rift.

The area between San Ysidro and the Jemez volcanic field to the north consists of a complex sequence of en echelon faults that run north and northeast. The main boundary faults on the west side of the rift are the Sierrita, Jemez and San Ysidro faults that are downthrown to the east with stratigraphic separation up to 685 m. These faults join and at some localities are connected by northeast-trending en echelon high -angle faults. The main western boundary fault appears to be a curved surface that flattens with depth (Woodward and DuChene, 1975) and probably dies out at depths of 10-15 km where plastic laminar deformation may occur (Woodward, 1977). Rotated beds and antithetic faults adjacent to the master boundary faults suggest about 8 km of crustal extension in a northwest-southeast direction, giving an annual rate of about 0.3 mm/year since initiation of rifting about 26 m.y. ago (Woodward, 1977).

Rocks exposed along this margin of the rift range in age from Precambrian to Tertiary (Santa Fe Group) with mainly Paleozoic rocks on both sides of the boundary faults. Thus, this margin of the rift is defined by faults rather

than by the distribution of sediments contemporaneous with rifting (i.e., Santa Fe Group). Hot springs and hot spring deposits are widespread along this part of the rift margin. Cenozoic volcanic rocks are absent except for those of the Jemez field. It appears that hot water reservoirs are probably limited here and that geothermal waters could be useful only for limited space-heating.

The western margin of the rift exposed north of the Jemez volcanic field near Coyote has been mapped by Woodward and Timmer (1979). The boundary fault in this area is covered by alluvium along Coyote Creek, but stratigraphic units indicate a fault with Morrison Formation (Jurassic) on the east and Abo Formation (Permian) on the west. Volcanic rocks of the Jemez field (Bandelier Tuff) are not cut by the fault, and no other volcanics occur along this fault.

Hot springs, hot spring deposits and rock alteration were not observed, suggesting that geothermal potential is very slight. This mapping ties in with that of Lawrence (1979; Appendix 2, this report) to the northeast; this area is discussed in the following section.

The Abiquiu Formation and the Zia Sand Formation were sampled jointly by Woodward and H. R. DuChene of Amoco Production Company. Palynomorphs from these units are now being studied by palynologists from Amoco to more precisely date these rocks in an attempt to determine the initiation of basin subsidence and rifting. Initial results indicate that both units are Miocene and essentially contemporaneous.

GEOCHEMISTRY

Water Geochemistry

Reconnaissance studies of the chemistry of spring waters from this area are compiled in Table 3 and Appendix 6 and are summarized in the section on regional water geochemistry.

Oxygen Isotope Geochemistry

Surface temperature, field pH, and $\delta^{18}\text{O}$ data were obtained for thermal springs and related meteoric waters collected from the southwestern Jemez Mountains. The $\delta^{18}\text{O}$ results range from -16.76 permil for snow to -1.59 permil for Sulfur Springs bath (see Table 15). Average meteoric water in the area is approximately -14 permil. All water samples appear to have undergone some evaporation (rivers and open pools) or oxygen isotope exchange at depth (warm springs).

A correlation matrix (Table 15) shows a strong correlation between $\delta^{18}\text{O}$ and surface temperature (0.731) and pH (-.990) for spring waters. Increased temperature at the surface reflects possible higher temperature at depth and therefore, greater ^{18}O exchange with reservoir rocks. A decrease in field pH with increasing temperature suggests that the waters have dissolved H_2S from host rocks and(or) exhibit low pH as meteoric waters alter felsic igneous rocks at elevated temperature.

Using data on the $\delta^{18}\text{O}$ composition of whole rock samples from the Jemez Mountains and fluid inclusion temperatures (Landis, 1978), together with the data in this report, it is possible to determine the water-rock oxygen atom ratio in the reservoir, assuming isotopic equilibrium. Using a meteoric water of -14 permil, water-rock ratios in the southwestern Jemez Mountains are on the order of 0.10. Subsurface reservoir temperatures calculated from average ^{18}O whole rock values and the meteoric waters reported here are: 1) Jemez Springs, 91°C (GW-75-23); 2) San Antonio Springs, 79°C (GW-75-30); and 3) springs on the west side of the Nacimiento Mountains, 99°C (GW-75-19). Sulfur Springs gives seasonally dependent values of 167°C (GW-75-31) and 180°C (GW-77-5).

Table 15

Correlation Statistics (Multiple Linear Correlation)

Jemez Mountains Waters

A. $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ versus Temperature and pH : all data

	<u>pH</u>	<u>$\delta^{18}\text{O}_{\text{H}_2\text{O}}$</u>
Temp	-0.411	0.345
pH		-0.879

multiple correlation: 0.773

B. $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ versus Temperature and pH : springs, $T > 30^\circ\text{C}$

	<u>pH</u>	<u>$\delta^{18}\text{O}_{\text{H}_2\text{O}}$</u>
Temp	-0.773	0.731
pH		-0.990

multiple correlation: 0.984

CONCLUSIONS

Geologic and geochemical studies suggest that the geothermal potential of the San Ysidro area is low. Because of this, no detailed geophysical studies were undertaken in this area. Oxygen isotope analysis indicates that springs on the west side of the Nacimiento Mountains may have sources in reservoirs with temperatures of about 100°C; this may be potentially attractive for local use. The Jemez Mountains, not studied here except at their margin, have been previously recognized (White and Williams, 1975) as a significant source of geothermal energy.

Abiquiu - Ojo Caliente Area

GEOLOGY

Abiquiu Area

Summary. The Abiquiu embayment is a western extension of the Espanola basin of the Rio Grande rift (Figure 76) (Woodward and others, 1978). The stratigraphic section of the area contains 1062 m of sedimentary rocks of Neogene age, the main reservoir for geothermal water, underlain by the Chinle and El Rito Formations of Late Triassic and Oligocene(?) age, respectively.

The El Rito Formation is a nonmarine sandstone about 140 m thick. The El Rito was deposited by south-flowing streams carrying reworked sedimentary clasts from local sources and metamorphic cobbles from the Brazos uplift. The Abiquiu Tuff (Miocene) is a continental sandstone up to 375 m thick which formed as a piedmont fan deposited largely by south-flowing streams which eroded the San Juan volcanic field. The Chama-el rito Member of the Tesuque Formation (Pliocene) is a nonmarine sandstone which exhibits evidence of local laharic deposition in its lower part. It is up to 600 m thick and was deposited by streams flowing south from the Brazos and San Juan uplifts. The Ojo Caliente Member of the Tesuque Formation (Pliocene) is an eolian sandstone derived from the Chama-el rito Member. The Tesuque Formation comprises the major portion of the Santa Fe Group in this area. The Espanola Formation is an eolian sandstone of Pleistocene age. Much of the area is covered by pediment gravels and eolian sand of Pleistocene age. See Wilson (1977; Appendix 2, this report) for details of the stratigraphy.

Most of the faults in the Abiquiu area, which are mainly of Pliocene age, strike northeast and are dowthrown to the east toward the Rio Grande rift, although antithetic faults are also present. The faults are normal, and their

Figure 76. Location of Abiquiu study area (shaded box) on generalized tectonic map of north-central New Mexico (modified from Woodward, Callender and Zilinski, 1975).

stratigraphic separation ranges from 3 to 380 m. They formed during rifting, although some may represent reactivated zones of Laramide weakness. Faults are locally intruded by olivine basalt dikes contemporaneous with extrusion of flows in the Jemez volcanic field to the south. Normal faulting of Holocene(?) age has a strike-slip component (Wilson, Appendix 2).

In early Miocene time, broad downwarping extended several kilometers to the west of the present structural border of the Rio Grande rift. About 1050 m of Santa Fe Group sediments were deposited in this basin before the culmination of rifting in the late Pliocene. Intrusion and extrusion of olivine basalt in the Pliocene were followed by local structural adjustments and pedimentation of Pleistocene and Holocene age.

Geothermal potential. Soldados spring, near the head of Madera Canyon about 15 km north of Abiquiu, is about 10°C warmer than the average annual temperature for the area (R. Shaeffer, personal communication, 1976). All other springs are cold. Laharic deposits in the Santa Fe Group require a local source of magma; one lahar has associated travertine deposits. These are the youngest manifestations of geothermal activity in this area. Locally faults have chalcedony, botryoidal chert and psilomelane deposited along their traces. All of the faults have secondary calcite associated with them; the amount of calcite appears to be directly proportional to fault density. On the basis of surface evidence, the geothermal potential of the area is apparently low.

Canones - Coyote Area

Summary. This area (Figure 77) sits astride the western boundary of the Rio Grande rift north of the Jemez Mountains. Normal faults forming this boundary divide the area from northeast to southwest, separating the Colorado Plateau on

Figure 77a. Location of Canones-Coyote area on generalized tectonic map of north-central New Mexico; study area outlined in bold lines (modified from Woodward, Callender and Zilinski, 1975).

Figure 77b. Tectonic and generalized geologic map of Coyote area, north-central New Mexico (from Lawrence, 1979; Appendix 2, this report).

Figure 77c. Tectonic map of the Canones area, north-central New Mexico (from Broomfield, 1977; Appendix 2, this report).

the northwest from the Rio Grande rift on the southeast. Rocks exposed on the Colorado Plateau are Permian through Cretaceous in age and include the Permian Cutler Formation, the Triassic Chinle Formation, Jurassic Entrada Sandstone and Todilto and Morrison Formations, and the Cretaceous Dakota Formation. Rocks of the rift include more than 1000 m of Oligocene(?) El Rito formation, Miocene Abiquiu Formation and early to middle Pliocene members of the Santa Fe Group. These Tertiary units outcrop west of the present structural boundary of the Rio Grande rift and apparently define Tertiary depositional basins which extended west of the rift. The entire section dips gently eastward, toward the Rio Grande rift, and has been broken by high-angle normal faults reflecting structural deformation during Late Cretaceous and mainly late Cenozoic time.

Volcanic rocks cap the mesas in the southern part of the area. The majority belong to the Polvadera group, the younger of two basalt-andesite--dacite-rhyolite associations present in the Jemez Mountains. The basaltic member of the group, the Lobato Basalt, contains olivine-augite basalt and augite-olivine basalt. The andesitic member, the Tschicoma formation, is made up of andesite, dacite, latite and quartz latite flows which characteristically contain plagioclase xenocrysts and ultramafic xenoliths. The rhyolitic member of the Polvadera Group is not present in this area. Limited exposures of the lavas of El Alto, Pliocene to Pleistocene basaltic andesite flows containing ultramafic xenoliths, occur in the southeastern corner of the area. Igneous intrusions ranging in composition from picrite through andesite occur along fault planes and in close association with faults in the eastern half of the area.

Volcanism in the area was concurrent with the latter stages of rift development and occurred over a 10-m.y. period, beginning in the late Miocene.

Extrusive centers appear to have been controlled by faults which bound the Espanola basin. Olivine basalt (49.2% SiO_2) of the Lobato Formation, and a picrite basalt dike (44.9% SiO_2), are classified as high-alumina, high-silica alkali basalts. Calc-alkaline andesites (56.4–59.5% SiO_2) of the Lobato Formation are olivine bearing, generally with both ortho- and clinopyroxene present. Chemical trends and progressive phenocryst development in successively younger flows suggest magmatic differentiation in the Lobato andesites exposed at Encino Point. Unconformably overlying the Lobato Formation are coarsely porphyritic calc-alkaline andesite flows and extrusive centers of the Tschicoma Formation, containing about 61% SiO_2 . These are in part capped by hornblende and hornblende-biotite dacites (65.1% SiO_2) which locally form small domes and were mapped as the upper member of the Tschicoma. Remnant outliers of the Bandelier Tuff (76.3% SiO_2) unconformably overlie most lower units.

Intermediate volcanic rocks become more differentiated upsection as well as laterally toward the east in the area. Progressive phenocryst development and probably cognate inclusions are interpreted as evidence of crystal fractionation. Calc-alkaline andesite eruptions appear to have been contemporaneous with minor alkali basalt volcanism. Earliest volcanic activity is recorded by the presence of picrite basalt bombs in a conglomerate of upper Santa Fe sandstone. See Broomfield (1977) and Lawrence (1979) for details on the stratigraphy (Appendix 2).

Two distinct episodes of tectonic activity in the Coyote area can be seen in high-angle normal faults of weak to locally moderate intensity. A system of north-trending faults, which displace pre-Tertiary strata and have an average vertical separation of 115 m, indicates movement during the Laramide, in Late Cretaceous to Eocene time. Several faults of this system appear to have been

reactivated during the Tertiary. A superimposed zone of younger, northeast-oriented curvilinear faults, with an average throw of 50 m, are late Cenozoic in age and form the western structural margin of the Española Basin. The curvilinear traces of these faults suggest the possibility of listric faulting with diminishing dips at depth. Small displacements in the Bandelier Tuff suggest Quaternary movement. Structural analysis indicates mainly vertical crustal adjustment along high-angle normal faults during the Laramide. Subsequent late Cenozoic tectonic movement was also vertical, however, with considerable extensional dip-slip motion associated with curvilinear faults.

The major structural features of the Canones area are normal faults trending northeast, most of which are down to the southeast. One of these faults is a curved fault which flattens with depth, based on inferred dips of the fault and the presence of "reverse drag." This listric fault, and others in the area for which evidence is less conclusive, implies a horizontal, east-west extensional stress field. As most of the faults displace the early to middle Pliocene Santa Fe Group but do not displace middle and late Pliocene volcanic rocks, they must be approximately middle Pliocene in age. Some of the faulting occurred later than this, as the last movement on one fault was during the late Pliocene deposition of the Tschicoma Formation.

Geothermal Potential. Evidence of geothermal activity in the Canones area is seen in the form of volcanic rocks, calcite, chalcedony, travertine, manganese oxide deposits and hydrothermal alteration of sediments. Almost all of these features are spatially related to faults. There are a number of springs in the area, but none are above the average annual temperature of the area.

Travertine occurs in only one locality, on the horst block at the north end of Canones Mesa. The spring which deposited the travertine is no longer active.

Calcite is present in many of the dikes in the area and in the rocks surrounding the dikes. It is apparently related to hydrothermal fluids ascending along the same paths as the dike material. Chalcedony and psilomelane are most obvious at the intrusive complex north of Tower Mesa. Hot springs must have been active in this area at some time, since besides the chalcedony and psilomelane, hydrothermal alteration occurred in the center of the complex and also near its edge close to the location of a presently active, but not warm, spring where a basaltic intrusive rock has been reduced to a mound of greenish dirt.

The most obvious alteration of sediments is seen in the Dakota Formation near Canones where the unit is a rusty color and a fault has been filled with veins of selenite. The most logical source of the gypsum is the Todilto Formation, which lies below the Dakota Formation. Hydrothermal fluids could have leached the gypsum and carried it upward to deposit it in the Dakota. The rusty color, which is only seen in the Dakota near faults in the study area, is also apparently the result of hydrothermal alteration.

Currently there appears to be no geothermal activity in the area. Although numerous springs are present, none is warmer than would be expected. On the basis of hot spring activity and surficial geology, it appears that the geothermal potential of the area is low. According to Trainer and Lyford (1979), dilution of thermal waters by cold underground water may be significant in this region.

Geothermal activity in the Coyote area was associated with local volcanism which began to fade with the most recent eruptions of the Tschicoma Formation, at least 3.7 m.y. ago (Bailey and others, 1969). No heat flow or surface-water temperature data are available from the study area, and none of the numerous

active or intermittent springs, commonly localized near faults, are presently known to carry thermal waters.

Indication that geothermal fluids were at one time active is suggested by the strong oxidation of volcanic rocks in and near extrusive centers and by weak silicification (SiO_2 veinlets) or calcification along some faults. The tuffaceous sandstone and volcanic conglomerate in the upper Santa Fe Group, north of Encino Point, have been subjected to intense calcite and zeolite alteration which is related to local extrusive and intrusive igneous activity. There is a lack of silica alteration, travertine deposits, manganese mineralization or other geothermal indicators throughout the Coyote area. Despite favorable factors, such as the availability of water, sufficient aquifers for water transport and a high density of faults, along which there is a strong possibility of structural traps being formed at depth, the potential of a shallow geothermal source in the area is considered low.

Ojo Caliente-Rio Chama Area

Summary. The Ojo Caliente-Rio Chama area lies in the northwestern Espanola basin of the Rio Grande rift (Figure 78) and exposes sandstone, conglomerate and volcanic debris that were washed into the basin from surrounding highlands during the late Tertiary and Quaternary. Tertiary sedimentary rocks exposed at the surface range from lower Miocene Ritito Conglomerate to upper Pliocene Totavi Lentil of the Puye Conglomerate, with a minimum total thickness of 1,050 m for the Neogene section. In the subsurface, an additional 600 to 1,200 m of mid-Tertiary basin-fill sediments probably overlie Precambrian basement to the southeast near the basin axis. The oldest exposed major basin-fill unit is lower Miocene Abiquiu Tuff, a tuffaceous sandstone probably deposited by a large alluvial fan complex with its sources northeastward in the rhyolitic to

Figure 78a. Generalized geologic map of Espanola basin and vicinity showing location of Ojo Caliente-Rio Chama area (Figure 3 of May, 1980; Appendix 2, this report); map modified from Woodward, Callender and Zilinski, 1975).

andesitic volcanic field of the Taos-Questa area and northwestward in rhyolitic to andesitic rocks of the San Juan volcanic field. The upper Abiquiu grades northward and upward into the Cordito Member of the Los Pinos Formation, a thick alluvial fan deposit of tuffaceous sand and gravel eroded from the San Juan volcanic field in the north during the Miocene. South of Ojo Caliente, the Los Pinos grades into the mid-Miocene Chama-el rito Member of the Tesuque Formation, which was simultaneously forming a west-sloping arkosic bajada transported westward by streams flowing away from the Sangre de Cristo uplift. A 13-m.y.-old field of basaltic tuff rings and tuffaceous spatter cones occurs in the middle of the Chama-el rito. The Ojo Caliente Sandstone Member of the Tesuque Formation represents a field of sand dunes that was deposited over the Chama-el rito by prevailing westerly winds during the mid-Miocene. The upper Miocene Chamita Formation is a thick unit of arkosic sandstone that unconformably overlies the Ojo Caliente Sandstone and was deposited by gently flowing streams originating in the Sangre de Cristo highland. The Totavi Lenticle of the Puye Conglomerate is a thin gravel layer deposited by either the late Pliocene axial Rio Grande or streams crossing a large planar erosion surface graded to the ancestral Rio Grande. At Black Mesa, the Totavi is overlain by a tongue of Servilleta Basalt that flowed southward from the Taos volcanic field along the valley axis in the late Pliocene. See May (1980; Appendix 2, this report) for details of stratigraphy.

Tertiary rocks are exposed in a gently southeast-dipping homocline that is part of the western limb of the synclinal Espanola basin and which exhibits approximately 1,250 m of structural relief on upper Tertiary rocks between the west and east sides of the area. Gravity data indicate approximately 3,000 m of relief on the Precambrian surface between Cerro Colorado and the basin axis

beneath Black Mesa. Numerous N.25E.-trending late Pliocene faults, many of which are antithetic to the basin, cut the homocline and down-fault the lower Ojo Caliente against the Chama-el rito throughout much of the area. Throws of 3 to 90 m are typical of most faults. Most faults are approximately planar, high-angle normal faults with minimal oblique-slip components of movement. The Ojo Caliente fault zone parallels the west side of Rio Ojo Caliente and downthrows the lower Ojo Caliente Sandstone in the west against the upper Chama-el rito in the east with up to 240 m of throw. To the north, an east-tilted horst of Precambrian crystalline rocks in the southern nose of the Brazos uplift plunges south beneath the Tertiary sediments of the basin. The horst is bounded on the west by a major normal fault that has downdropped the Ojo Caliente Sandstone against the Precambrian with up to 670 m of throw. Numerous broad, ill-defined flexures in the faulted Tertiary rocks indicate vertical and slight rotational motion in the crystalline basement rocks during the late Tertiary, when northwest- to southeast-directed crustal extension produced widespread block faulting and subsidence in the basin. Hot springs, possible mid-crustal magma chambers, recent volcanism and zones of modern subsidence and earthquakes indicate that the basin is still tectonically active.

Geothermal potential. The presence of travertine deposits and hot springs in the Ojo Caliente-La Madera area suggests locally significant geothermal activity. In 1979, the Bureau of Land Management made 570 km² of public land available to leasing for geothermal exploration in the Ojo Caliente area. The following discussion is a brief evaluation of the possibility that economic amounts of hot water and steam underlie the northern part of this area. Because of the general lack of subsurface information, this evaluation is based

primarily on study of the surface geology (May, 1980 and Appendix 2). The geothermal model proposed here for the Ojo Caliente area will require further refinement or revision when more subsurface information becomes available.

The northwestern part of the Espanola drainage basin receives groundwater recharge from the Brazos uplift in the north, where rainfall is approximately 36 cm per year (Bureau of Land Management, 1978). Surface runoff from the uplift forms Rio Ojo Caliente and El Rito Creek, which probably lose some of their water by infiltration as they flow south across the permeable Tertiary clastic rocks of the basin. Infiltration of rainfall into the sediments contributes additional water. Hence, most, if not all groundwater in the basin is meteoric in origin. Water wells in the map area indicate a gently southward sloping water table that is generally less than 91 m below the surface except in areas of high relief (Bureau of Land Management, 1978). The groundwater in basin-fill aquifers probably flows southeastward over less permeable crystalline basement and eventually discharges into the Rio Grande.

Evidence of Quaternary geothermal activity in the region is restricted mainly to the Pliocene Ojo Caliente fault zone between Rio Chama and the La Madera area. The northeasterly trend of the hot springs and mineralization indicates strong structural control of the rising hot water system in the upper crust by the northeast-trending Pliocene faults and suggests a Pliocene (?)—Recent age for most of the geothermal activity.

From Ojo Caliente to La Madera, the Precambrian basement of the Brazos uplift is near or at the surface, and numerous northeast-trending faults and joints of the Ojo Caliente fault zone appear to form conduits for the rising hot water. All hot springs and travertine deposits in the region are restricted to this part of the fault zone. The Ojo Caliente hot springs consist of five groundwater seeps (one cold) that flow from the base of a

prominent northeast-trending ridge of Precambrian metarhyolite west of Ojo Caliente. The two most prominent joint sets in the metarhyolite ridge have average orientations of N.45E., 60°E. and N.70W., 80°N., and probably control flow of the thermal waters locally. A possible northeast-trending fault beneath the alluvium and Los Pinos Formation parallels the ridge and may also provide a conduit for rising thermal water. The regional metamorphic foliation in the metarhyolite is approximately N.55E., 70°E. but probably does not effect groundwater movement as much as the joints and fault, because it does not appear to produce significant porosity and permeability in the crystalline rock. Temperatures of the springs reported by previous workers range from 32 to 50° C. On the basis of deuterium/oxygen 18 analyses, Trainer and Lyford (1979) estimated mixing proportions of 17 percent hot water/83 percent cold water for the springs and an original temperature of 188° C for the hot water.

Further description of the springs is given by Summers (1976). Minor travertine, white calcite, gypsum and salt (?) stain local outcrops and have cemented the terrace gravels on the west side of Rio Ojo Caliente between the hot springs and the mouth of Arroyo El Rito. The basal 6 to 15 m of the Ojo Caliente Sandstone east of town has also been cemented locally.

South of Ojo Caliente, the Ojo Caliente fault zone exhibits weaker evidence of geothermal activity. All springs in this area are cold and are listed in Table 16. Pervasive calcite- and gypsum-cemented zones parallel the faults and generally occur on the downthrown sides of the faults in the porous Ojo Caliente Sandstone. A few minor veins of black and white opalite occur at Cerrito de la Baca and along a fault between Cerro Negro and Arroyo El Rito. The largest opalite-calcite deposit occurs as vein-filling east of the Ojo Caliente tuff ring but may reflect only a local source of volcanic silica.

Table 16

List of cold springs in the Ojo Caliente-Rio Chama area (from May, 1980)

1. Dry spring along northeast-trending fault: indicated by small grassy area: very little CaCO_3 cementation: may flow when water table high: southeast side of Sierra Negra: 0.35 miles (0.56 km) N. 15 E. of northwestern corner of Carson National Forest.
2. Slow trickle of spring water at mouth of Arroyo de Agua: source of water in NW $\frac{1}{4}$ sec. 12, T. 22 N., R. 8 E. Local terraces and Quaternary alluvium of Rio Chama are cemented with white calcite and gypsum.
3. Spring forms a swamp in valley floor of Cañada de los Alamos: all rock units except Quaternary alluvium are partly cemented: spring possibly related to northeast-trending fault in lower Ojo Caliente Sandstone: 2.2 miles (3.5 km) N. 5 W. of confluence of Rios Chama and Ojo Caliente: NW $\frac{1}{4}$, NE $\frac{1}{4}$ sec. 13, T. 22 N., R. 8 E.
4. Spring issues from north-trending fault: 0.6 miles (1 km) N. 10 E. of confluence of Rios Chama and Ojo Caliente: SE $\frac{1}{4}$, SE $\frac{1}{4}$ sec. 24, T. 22 N., R. 8 E.
5. Several cold springs drain from lower western slopes of Black Mesa according to Dorothy Fredricks who lives at Shadow Mountain, 1 mile (1.6 km) N. 10 E. of Vallito Peak.
6. Grassy area on floor of Cañada de los Alamos indicates near-surface groundwater: spring may flow when water table high: cemented late-Pleistocene terrace remnants of Rio Ojo Caliente 0.5 miles (0.3 km) east and northeast of spring indicate recent groundwater movement: SE $\frac{1}{4}$, sec. 29, T. 23 N., R. 8 E.

In summary, meteoric water at high elevations in the Brazos uplift probably descends through fractures in the crystalline basement to a deep thermal source, possibly heated by conduction from either the mantle or an underlying body of magma. The association of hot springs with northeast-trending Pliocene faults in the area may indicate that Laramide and late Pennsylvanian faults were sealed off to groundwater flow by mineralization prior to Pliocene rifting of the Espanola and San Luis basins. Heated water rises by convection, probably as a result of its slightly lower density and a possible hydrostatic head between Ojo Caliente and the higher elevations to the north.

The lack of hot springs farther south in the basin may result from the large circulating reservoir of cold meteoric water in the porous Tertiary basin-fill deposits, above the less permeable Precambrian crystalline rocks.

Here, thermal water rising along fractures in the basement enters the overlying reservoir of meteoric water and is cooled by mixing. Permeability along the Pliocene-Quaternary rift faults in the sediments allows further upward movement of the diluted water and precipitation of the dissolved constituents in fractures, producing the cemented zones along the southern Ojo Caliente fault zone.

At Ojo Caliente, the hot water rises to higher elevations along the fractured but more tightly sealed crystalline rocks which contain less near-surface water for dilution. The hot water discharges at elevations slightly above the surrounding water table because of convective pressure and the relatively sealed fracture system in the crystalline rocks.

According to this model:

1. Cold meteoric groundwater in the basin-fill sediments tends to mask the presence of a deep geothermal system because of dilution. Therefore, thermal gradients measured in shallow holes will not be indicative of those at greater depths.
2. The shallowest drilling depths to hot rock might be expected in uplifted blocks in which the overlying basin-fill sediments have been removed. The area of hot springs between Ojo Caliente and La Madera may be the most favorable area to drill according to this model. Furthermore, in the recently uplifted Brazos area, the elevated isotherms of the uplift may not have had time to equilibrate with the regional geothermal gradient, thereby contributing additional heat to the rising water.

CONCLUSIONS

Based on detailed geologic studies, the geothermal potential of the Abiquiu-Ojo Caliente area is low. No detailed geochemical or geophysical studies were carried out in this area. All manifestations of geothermal activity such as hot and cold springs, spring deposits and volcanic centers, are strongly controlled by Neogene structural features associated with the Rio Grande rift. Most geothermal activity is Pliocene in age. The most significant geothermal potential in this area probably exists near Ojo Caliente, where dilution by cold groundwater is minimal and elevated isotherms in Precambrian basement may be preserved.

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